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ULTRA-WIDEBAND RADAR

Research and Development Considerations

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GLOSSARY

DoD	Department of Defense
EM	electromagnetic
EMP	electromagnetic pulse
ESD	Electronic Systems Directorate, USAF
FFT	fast Fourier transform
FM	frequency modulation
HPM	high-power microwave
HDL	Harry Diamond Laboratory
ICBM	intercontinental ballistic missile
IEEE	Institute of Electrical and Electronics Engineers
ISRD	Institutional Supporting Research and Development
LAMPF	Los Alamos Meson Physics Facility
LANL	Los Alamos National Laboratory
LHS	left-hand side
LO	low observable
LPI	low probability of intercept
MMW	millimeter wave
NAVSEA	Naval Sea Systems Command
NCTR	noncooperative target recognition
NOSC	Naval Ocean Systems Center
NRL	Naval Research Laboratory
ODE	ordinary differential equation
ONT	Office of Naval Technology
OPNAV	Office of Naval Operations
OTH	over-the-horizon
PCPS	photoconductive power switch
PDE	partial differential equation
PIN	P-type—intrinsic—N-type
PRF	pulse repetition frequency
RADC	Rome Air Development Center
RCS	radar cross-section
SAR	synthetic-aperture radar
TEM	transverse electromagnetic
USN	United States Navy
UWB	ultra-wideband

Executive Summary

This report provides an initial investigation into the technology of impulse radar. The principal purpose is to provide a road map for exploratory development by defining critical technology issues for a research investment strategy.

There are urgent requirements for improving radar capability for target identification, or noncooperative target recognition (NCTR). Progress in NCTR has been primarily in information processing, with few technology advances in the sensor domain. Impulse radar provides new and revolutionary ideas, which can offer new capabilities for active surveillance. These capabilities are discussed in this report along with issues that must be resolved before system development is undertaken.

Background

Radar, in its many variations, is a mature and sophisticated technology. The capabilities of current radar systems are, however, inadequate for many important applications such as target identification, detection of "stealth" targets, and target imaging.

Recent advances in high-speed high-power switching devices have provided the technology base for innovative radar concepts that will discriminate targets by radar signature. These impulse-radar concepts have lacked substantive investigation heretofore.

The idea of transmitting an impulsive waveform of very high peak power with a frequency spectrum extending from almost dc to beyond 1 GHz introduces a revolutionary concept for wideband radar design. There are several potential advantages and advanced capabilities of such a radar as compared with conventional narrow-band radar.

- High-resolution range measurement (1 ns $\Rightarrow$ 15 cm)
- Significant target-discrimination and target-identification capability

- Detection of low-observable (LO) targets (low-RCS and stealth)
- High-resolution target-imaging capability (single and multiple targets)
- Improved penetration capability (earth, walls, foliage)
- Ultra-short-range capability
- Rejection of clutter and multipath interference through range gating
- Low probability of intercept and low probability of exploitation
- Reduced sensitivity to electronic-warfare countermeasures

Ultra-Wideband Technology

The technology of ultra-wideband (UWB) radar differs greatly from that of conventional radar.

- The relative bandwidth of impulse radar is large and requires analysis of the launching, propagation, reflection scattering, and reception of *transient* electromagnetic (EM) waves rather than the much simpler steady-state sinusoids, which suffice for narrow-band systems such as conventional radar.
- New antenna designs must be undertaken for transient waves, which require starting from *basic principles* (Maxwell's equations), as standard antenna theory is based on sinusoidal excitation.
- New devices, such as the laser-activated *photoconductive power switch* (PCPS), require development for high-power pulse generation at high pulse-repetition rates. Some of this development is already in progress.
- New concepts are required in receiver and transmitter designs, such as the *channelized receiver* combined with *rise-time control* of high-power pulse generators for controlling the radiation field.
- Studies in *materials science* are required for UWB radomes and for dielectrics used in the high-power sections of an impulse radar.

- Emphasis is required on *time-domain* electromagnetics in measuring and computing impulse response of targets, radar-absorbing materials, transmitting and receiving antennas, radomes, and various media.
- New *signal-processing* algorithms must be developed for impulse radar.
- Potential applications of impulse radar require a variety of *systems analyses and simulations* to investigate optimum signal and antenna design, EM response of targets, jamming and countermeasures, clutter rejection, false alarms, EM compatibility, detectability, performance evaluations and comparisons.

Recommended Program of Impulse-Radar R&D

- A collection of R&D initiatives is recommended to examine the basic system and technological issues requiring investigation prior to system development. Some of the more important tasks include (1) low-power short-range measurements of transient EM response of various targets and materials, (2) transient measurements of proposed antenna designs, (3) determination of the need for revised PCPS designs to provide rise-time control, (4) study of the ability of the channelized receiver to provide rapid selection of various matched filters and to counter jamming, (5) study of radome materials for use over extremely wide bands, and (6) EM analysis and computation for antenna design, transient scattering, and parametric system design.
- A parallel study of potential applications of impulse radar is needed to guide the R&D program in technology and to select an application for early prototype development.
- With sufficient answers to the technological questions, initiate the development of a prototype impulse radar for the application selected in the system study.

The broad range of *critical* areas that can be effectively addressed with this research approach can be categorized as follows.

- Overall system design, analysis and simulation
- UWB-radar transmitting and receiving antennas
- EM propagation of UWB waves
- EM response of targets to impulse-radar signals
- UWB-radar target identification
- UWB-radar imaging of targets

The research areas listed above are described in detail in the body of this report and are essential to the development of advanced radar capabilities using impulsive signals.

Contents

List of Figures

Chapter 1

Introduction

Radar, in its multiplicity of realizations, is a mature and sophisticated technology. The capabilities of current state-of-the-art radar systems are, however, inadequate for many important advanced requirements, such as target identification, "stealth" target detection, target imaging, and material penetration. These inadequacies do not necessarily result from limitations in current hardware technology, but they are largely due to limitations and difficulties inherent in the basic process of radar itself. The inherent difficulties of the radar process, as a technique of remote sensing, result primarily because the radar process is an *inverse problem*. Therefore, extracting significant information about a target from the returned radar signal is an exceedingly difficult and sensitive problem of a *mathematical nature*. That is why the achievement of advanced radar capabilities *will not* result simply from advancements in hardware technology but will also require advancements resulting from theoretical research in fundamental areas such as EM theory, systems theory, and signal analysis.

In order to make efficient progress in the development of any capability based on a complex physical process, a fundamental and complete understanding of the overall problem is necessary. In the case of advanced, remote-sensing capabilities based on UWB radar, the processes involved are varied and highly complex. Although much information can be obtained through experimental development, this

information can only allow an empirical, and therefore limited, approach to further development. In order to gain a fundamental understanding of the complex processes involved so that a knowledgeable and efficient approach to development can be undertaken, it is necessary to formulate and solve the complex mathematical problems that define these processes and to develop a theoretical understanding of the problem. For this reason, the achievement of advanced radar capabilities based on UWB approaches will require a strong theoretical effort.

A number of potentially significant approaches to the achievement of advanced radar capabilities are based on the use of UWB signals, of which *impulse radar* is a specific example. Fundamentally, these approaches are based on the concept of using signals having a temporal structure that is significantly different from that of *conventional* radar signals. The temporal structure of a conventional radar signal is often an amplitude-modulated sinusoidal wave. The modulation generally takes the form of a broad envelope containing many cycles of the single-frequency sinusoidal carrier. Therefore, the signal has a small relative bandwidth (narrow power spectral density). UWB radar approaches are based on signals having a large relative bandwidth (broad power spectral density). The concept of impulse radar suggests the use of a signal consisting of very short pulses, i.e. "impulses" having a large relative bandwidth. Many temporal structures for UWB radar signals are possible, all of which remain to be examined carefully to determine their potential benefits and capabilities. In this report, the broad term *UWB radar* is used to include impulse radar as well as a number of other important concepts that are not necessarily based on an impulse structure, such as "chirp" radar and other *spread-spectrum* approaches [Cooper and McGillem 1986].

Some of the potential advantages and capabilities that are attributed to UWB radar as compared with conventional narrow-band radar are the following.

- High-resolution range measurement (1 ns $\Rightarrow$ 15 cm)
- Significant target-discrimination and target-identification capability
- Detection of low-observable (LO) targets (low-RCS and stealth)
- High-resolution target-imaging capability (single and multiple targets)
- Improved penetration capability (earth, walls, foliage, rain)
- Ultra-short-range capability
- Rejection of clutter and multipath-interference through range gating
- Low probability of intercept (LPI) and low probability of exploitation
- Reduced sensitivity to electronic-warfare countermeasures

Of these items, target identification, LO target detection, and target imaging are of particular importance; however, a detailed understanding of the best ways to achieve these potential advantages and capabilities remains to be developed.

Many of the basic *hardware requirements* for a UWB radar system are understood in general and much of the required *hardware technology* is currently available. Therefore, many of the hardware aspects of UWB radar are of an engineering specification and design nature. Other hardware aspects will require some engineering research and development, but these steps cannot proceed effectively until detailed design requirements are determined. The problem of immediate concern is that fundamental questions regarding the basic process and potential capabilities of UWB radar currently *do not* have clear and detailed answers. Many questions must be answered before the system-design and hardware-development process can be knowledgeably and effectively undertaken.

Of critical importance, therefore, is the formulation, solution, and analysis of problems describing the fundamental physical processes, which are problems in EM theory requiring a strong mathematical approach, and the development and

application of state-of-the-art system analysis and signal analysis. One goal of the needed research is to provide for the knowledgeable design of a UWB-radar signal structure for a particular application to obtain a high level of performance.

The development of impulse radar is a multifaceted task requiring research in a number of technical areas. Research to determine the fundamental characteristics and advantages and the potential capabilities of impulse radar is essential at this time. The research areas outlined in this report are designed to address a number of important and fundamental problems. This work is critical to the efficient development of advanced radar capabilities based on UWB concepts.

The performance of theoretical research in UWB radar based on system modeling and analysis, transient EM theory, and signal analysis will answer many important questions. This work will result in a fundamental understanding that is critical to the efficient development of advanced radar capabilities based on UWB concepts. This research approach entails complete and detailed "system modeling" and is based on solving in detail the fundamental EM problems and on applying state-of-the-art system analysis and signal analysis. In some cases, the basic ideas under consideration can also be demonstrated with low-power proof-of-principle experiments. This research can then be followed by engineering analysis and design.

The broad range of *critical* areas that can be effectively addressed with this research approach can be categorized as follows:

- Overall system design, simulation, and analysis
  - impulse signal design
  - signal-encoding schemes (random, orthogonal, cyclic difference set, etc.)
  - signal recognition and discrimination algorithms
  - coherent matched-filter design and analysis
  - noise and interference modeling and analysis
  - signal intercept and detection analysis

- UWB-radar transmitting/receiving antennas
  - UWB antennas for "impulsive" signals
  - arrays of UWB antennas
  - antenna structures for launching "focus-wave" propagation modes
- EM propagation of UWB waves
  - signal-propagation characteristics (attenuation, dispersion, skipping, ducting, surface modes, etc.)
  - focus-wave and "electromagnetic-missile" propagation modes
  - propagation through materials, plasmas, rain, dust, etc.
  - EM interactions with matter
- EM response of targets to impulse-radar signals
  - transient EM scattering theory
  - transient EM response of LO targets
  - screened and embedded targets, material penetration
  - resonance, surface waves, "delayed" returns, etc.
  - time-domain reflectometry and homomorphic system theory
  - signal design for UWB-radar target identification
- UWB-radar target identification
  - transient inverse EM scattering theory
  - time-domain identification signatures
  - spectral system identification
  - parametric system identification
  - singularity-expansion-method approaches
  - resonance-mode and surface-wave-mode identification
- UWB-radar imaging of targets
  - UWB synthetic-aperture approaches
  - image reconstruction as time-domain reflectometry
  - image reconstruction by ellipsoidal backprojection

These items represent a number of research areas that are essential to the development of advanced radar capabilities utilizing UWB signals. Many of these items also represent areas of research that are currently of great interest in the disciplines of electrical engineering and applied mathematics.

In conclusion, the advanced radar capabilities that are potentially achievable using UWB approaches are currently uncertain and, therefore, *system modeling, mathematical analysis, and proof-of-principle experiments that elucidate potential capabilities are of great importance*. These topics and others will be addressed in more detail in the remainder of this report.

Chapter 2

Why Ultra-Wideband Radar?

UWB radar is considered to be any radar system in which the *relative bandwidth* of the signal is larger than about 10%. If the upper and lower useful frequencies of the signal power spectral density are denoted by f_u and f_l respectively, the relative bandwidth R is defined as $(f_u - f_l)/(f_u + f_l)$. This definition is useful not only for conventional radars but also for impulse radars where no carrier frequency appears. To understand the theoretical basis for and the practical application of UWB radars it is necessary to consider first the theoretical limitations on conventional sinusoidal-carrier radars. These limitations suggest that certain aspects of radar performance can be improved only by creating radar systems that use UWB signals.

2.1 Overview of Conventional Radar

Conventional radar is one in which a sinusoidal carrier is amplitude modulated by a periodic sequence of short pulses. The sinusoidal carrier may or may not be coherent from pulse to pulse. If the carrier is coherent from pulse to pulse, the radar is called a pulse Doppler radar. Since the pulse Doppler radar is the most capable form of conventional pulse radar, it is this form that is considered in this overview.

2.1.1 Characteristics and Applications

The conventional pulse Doppler radar measures targets in four coordinates: range, range-rate, azimuth angle, and elevation angle [Golden 1987]. The capability of conventional radar is frequently expressed in terms of its resolution and its accuracy. The resolution of a radar is a measure of its ability to separate responses from targets differing from one another in one or more of the four coordinates. The required resolution in any coordinate depends on the application of the radar. Typical applications of pulse Doppler radar include early warning, area search, surveillance, target tracking, fire control, ground mapping, and target identification. Of these applications, the last one requires the greatest resolution in range and angles. As shown below, range resolution depends on signal bandwidth and this parameter is under the control of the signal designer. In contrast, Doppler resolution depends on the observation time, and angle resolution depends on antenna size. These parameters do not depend directly on the form of the transmitted signal.

2.1.2 Range Resolution

The range resolution of any radar depends entirely on the signal bandwidth and is frequently defined as [Burdic 1968]

$$\delta_R = \frac{c}{2\beta_e} \tag{2.1}$$

where $c = 3 \times 10^8$ m/s is the propagation velocity of light in free space. The parameter β_e is the effective bandwidth of the signal defined by

$$\beta_e = \frac{\mathcal{R}^2(0)}{\int \mathcal{R}^2(\tau)d\tau} \tag{2.2}$$

where $\mathcal{R}(\tau)$ is the autocorrelation function of the signal pulse. The range-rate resolution depends primarily upon the time interval over which the signal is observed and the angular resolutions depend on the radar antenna dimensions in the corresponding directions and the wavelength of the carrier frequency.

The accuracy with which measurements can be made in each of the four coordinates is also a function of the signal-to-noise ratio (SNR). For example, the range accuracy may be expressed as [Burdic 1968]

$$\sigma_R = \frac{c}{\beta_0\sqrt{2E/N_0}} \tag{2.3}$$

where E is the received signal energy, N_0 is the one-sided noise spectral density at the receiver input, and β_0 is the rms bandwidth defined by

$$\beta_0^2 = (2\pi)^2 \frac{\int f^2 S(f)df}{\int S(f)df} \tag{2.4}$$

in which $S(f)$ is the energy-density spectrum of the signal. The range-rate accuracy and the angular accuracy also depend on SNR in a similar way.

2.1.3 Limitations of Conventional Radar

The important point in the above equations is that both the range resolution and the range accuracy depend inversely upon the signal bandwidth. Since these are theoretical limits, no amount of clever signal design can replace this dependence on bandwidth. If one wishes to resolve closely spaced targets in range, the only way to do it is to increase the signal bandwidth. As seen below, both target identification and target imaging require extremely good range resolution.

Another important characteristic of periodically pulsed signals is the ambiguity function. This function reveals target ranges and target velocities at which there are ambiguous responses and indicates the existence of any coupling between range and velocity measurements. Ambiguous responses impose serious constraints on combinations of range and velocity that can be observed by the conventional radar.

2.2 Approaches to Ultra-Wideband Radar

There are two general approaches to increasing the signal bandwidth of a radar system. The first approach is referred to as *spread-spectrum* and consists of designing

signal waveforms that have a large bandwidth without decreasing the duration of each signal pulse. This requires some sort of modulation within the pulse. Such signals have a large time-bandwidth product. The second approach is to reduce the duration of each signal pulse. Signals of this type will have a time-bandwidth product near unity.

2.2.1 Spread-Spectrum Radar

A number of different techniques can be employed to create spread-spectrum signals. A brief discussion of each of these approaches is provided below.

1. **Stepped FM**

   In this type of signal, the frequency of the carrier is hopped in a pseudorandom fashion over a wide range of frequencies during each pulse. Although this approach has advantages in clutter reduction and in jamming resistance, the large range sidelobes make it unsuitable as a means for achieving good range resolution.

2. **Linear FM**

   The frequency of the carrier is swept linearly over a wide range of frequencies during each pulse. Excellent range resolution can be achieved through this approach, but a coupling between range and range-rate results in moving targets appearing at the wrong range unless suitable compensation is employed. This approach is frequently referred to as chirp radar.

3. **Nonlinear FM**

   Increasing the FM sweep rate near the edges of the pulse and decreasing it in the center can be used to lower the sidelobes of the signal spectrum. This is advantageous in the design of the corresponding matched filter.

4. **Pseudorandom Coding**

   The carrier is biphase modulated throughout the pulse by a pseudorandom binary sequence. This approach avoids the range-Doppler coupling of the FM signals, but may produce large range sidelobes unless the pseudorandom sequence is very long.

5. **Hybrid Methods**

   It is also possible to combine two of the above methods in order to achieve the advantages of each without (hopefully) the disadvantages of either. The most common hybrid approach is to add pseudorandom coding to each hop in a stepped FM signal.

6. **Random Signal**

   Still another method achieving extremely large time-bandwidth product signals is to transmit bursts of wideband noise. Signal detection is accomplished by cross-correlating the received signal with samples of the transmitted signals. Unlike any of the other methods, range sidelobes can be made arbitrarily small, and range and velocity ambiguities can be controlled independently.

2.2.2 Impulse Radar

The second approach to achieving a UWB signal is to shorten the pulse duration because the bandwidth is roughly proportional to the reciprocal of the pulse duration. This approach is the basis for *impulse radar* in which there is no carrier at all. The antenna is excited by a sequence of very short baseband current pulses. In order to achieve sufficient pulse energy to accomplish target detection at reasonable ranges, it is necessary that the peak power be very large.

While the relative bandwidth of spread-spectrum radar systems tends to be considerably less than unity, the relative bandwidth of impulse-radar systems is almost always close to unity. The spectrum of such a signal can easily span two or

three decades in frequency. Because of this unique feature of impulse radar, it is this approach to UWB radar that is discussed in detail in this report.

2.3 Potential of Ultra-Wideband Radar

The answer to the question, "Why UWB radar?", lies in the unique capabilities that such a radar approach may possess. Some of the potential advantages and advanced capabilities that have been attributed to UWB radar as compared with conventional radar are listed on page 3. Some of these capabilities are presented in more detail below.

1. **Target Identification**

   The extremely good range resolution that can be achieved by UWB radar make it well suited for advanced capabilities such as target identification. The typical target consists of a number of scattering regions whose responses are merged into a single return signal in a conventional radar system. In a UWB radar these distinct scattering regions can be separated, thus aiding in the identification of the target. Also, because of the broad spectral density, various target-response modes may be excited that may be used in identification.

2. **Detection of Low-Observable Targets**

   The use of UWB signals may aid in the detection of LO targets. Such LO "stealth" targets may be coated with radar-absorbing materials that perform well over only a relatively narrow band. UWB radar signals may be able to exploit this limitation. Alternatively, targets may be designed to have a low RCS by careful avoidance of flat surfaces, sharp edges, and any resonances in the usual radar bands. A UWB signal may uncover such resonances and produce a much larger return than would a conventional radar.

3. Target Imaging

A related task in which the UWB radar might be useful is that of target imaging, such as in a scanning mode or in synthetic-aperture radar (SAR). In general, target imaging requires both good range resolution and good angular resolution. The excellent range resolution is achieved by the use of UWB signals. The angular resolution, which depends either on antenna size or antenna motion, may be achievable directly for close targets or at a distance by employing a synthetic aperture. Image reconstruction techniques based on separated transmitters and receivers may allow high-resolution 3-D capability.

4. Penetration Radar

The use of impulse radar for ground penetration to detect tunnels, bunkers, mines, etc., has been widely proposed and appears to have considerable merit. A related application is the penetration of foliage to detect manmade objects that would otherwise be hidden from view. This application is of particular concern in locating strategically relocatable targets such as missiles, launchers, tanks, trucks, etc., which can be effectively hidden from conventional radar and infrared sensors by both foliage and camouflage.

5. Rejection of Background Clutter

The detection of targets in the presence of background clutter is always a challenging task. Often the good range resolution provided by the UWB radar can be exploited to separate the target from the clutter. In this regard, impulse radar is probably better than the spread-spectrum radar, because clutter can be eliminated by range gating rather than depending on the low correlation sidelobes of the spread-spectrum signal.

6. Low Probability of Intercept and Exploitation

The LPI capability of any radar is dependent upon the capability that one assumes for the intercept receiver. This is also true for impulse radar. However, an intercept receiver designed to detect the presence of conventional radar signals may not be effective in detecting the presence of an impulse-radar signal. Even if the intercept receiver employs energy detection (as it must in almost all cases), it will only detect the radar signal if it is observing in the right direction at the right time. Exploitation of a radar signal implies that the signal can be used to advantage by the object the signal illuminates. A common example of this is the use of radar homing by a missile in which the missile-guidance system homes in on the radar transmissions. Although there are numerous known countermeasures for this type of exploitation with conventional radars, most involve some sort of multimode operation. A radar system that could avoid such exploitation without requiring a change in the mode of operation would be advantageous. Impulse radar may provide such a system.

Chapter 3

Ultra-Wideband Radar

3.1 Theoretical Considerations

In order to make efficient progress in the development of any capability based on a complex physical process, a fundamental and complete understanding of the overall problem is necessary. In the case of advanced, remote-sensing capabilities based on UWB radar, the processes involved are varied and highly complex. Although much information can be obtained through experimental development, this information can only allow an empirical, and therefore limited, approach to further development. In order to gain a fundamental understanding of the complex processes involved so that a knowledgeable and efficient approach to development can be undertaken, it is necessary to formulate and solve the complex mathematical problems that define these processes and to develop a theoretical understanding of the problem. For this reason, the achievement of advanced radar capabilities based on UWB approaches will require a strong theoretical effort.

3.1.1 Time-Domain Electromagnetics

The solution of fundamental theoretical problems, predominantly through the discipline of applied mathematics, is of critical importance to the understanding and development of UWB radar. For the short-duration EM pulses to be used in impulse

radar, the solution of problems in antenna design, EM propagation, EM scattering, and the EM response of targets is of critical importance. For the achievement of advanced radar capabilities such as target identification and target imaging, inverse problems for transient EM scattering need to be formulated and solved.

Although highly developed frequency-domain approaches can be applied to these problems in transient EM theory, it is natural and more efficient to formulate these problems in the time domain [Bennett 1978, Ross 1986]. For almost all problems of importance to the development of UWB radar, the electrical parameters of the materials can be assumed constant with respect to the field amplitudes. Therefore, the mathematical formulation of the problem is linear and the equivalence, through the Fourier transform, of the frequency domain and the time domain holds. When factors such as computational efficiency are considered, however, formulating and solving these problems in the time-domain is crucial.

For effective formulation and solution, the transient electromagnetic processes in impulse radar require a time-domain approach rather than the frequency-domain approach traditionally used in engineering electromagnetics. The formulation and application of finite-difference, time-domain (FDTD) methods is an emerging numerical approach in computational electromagnetics (CEM). The FDTD solution of Maxwell's curl equations is analogous to the finite-difference solution of scalar-wave-propagation and fluid-flow problems in that the numerical model is based upon the direct solution of the governing partial differential equations. Another approach to solving Maxwell's equations in the time domain involves a Galerkin finite-element (GFE) formulation for irregular, nonorthogonal grids. Employing quadrilateral and/or triangular elements, the GFE approach allows more accurate modeling of nonrectangular structures. FDTD and GFE are nontraditional approaches in the field of computational electromagnetics, where frequency-domain integral equation approaches such as the method of moments have dominated for 25 years.

Because of the complexity of the physical processes involved, time-domain electromagnetic theory is of critical importance to and must be an integral part of the development of UWB radar. For this reason, an overview of time-domain electromagnetic theory and a quintessential problem in transient EM scattering are presented in Appendix A.

3.1.2 Emission, Propagation, and Penetration

The emission and propagation of EM waves having temporal variations that are nonsinusoidal is a subject that is not completely understood. Recently, there has been a considerable amount of discussion over the controversial ideas of Henning Harmuth concerning nonsinusoidal EM waves. See the *IEEE Transactions on Electromagnetic Compatibility* over the last 5 years. The ideas of Harmuth have some implications for impulse radar. To the extent that the authors have had time to check his work on transient propagation in lossy media, the results appear to be correct [Appendix C]. We cannot endorse all of his work on antennas, a subject which requires much further study.

The design of antennas for the emission of EM impulses is important to performance capabilities. A number of different approaches to UWB antenna structures are described in Section 3.2.2. The effective development of high-performance antennas will certainly require a considerable amount of EM modeling. Several computer codes exist that can be applied to this development. Thin-wire time-domain codes such as TWTD and its relatives [Landt 1974, Miller 1980] are immediately available for use in modeling certain antenna structures. Other time-domain codes that have been developed for particle-accelerator modeling, such as the MAFIA code group [MAFIA 1988] may be useful for electromagnetic scattering problems.

Recently, propagation modes that have a far-field energy distribution that remains "localized" have become of interest [Brittingham 1983, Wu 1985, Ziolkowski 1988]. These interesting propagation modes are referred to by a variety of names

such as "focus waves", "EM missiles", "directed-energy pulse trains", etc. The capability of directed-energy transfer in a radar system is of great potential importance. It is not yet known whether any of these ideas will find application in radar, but they certainly deserve further investigation.

The theory of the penetration properties of nonsinusoidal EM waves in lossy materials has been explored in some depth in the literature [Harmuth 1986]. However, this exposition is still very abstract. One can draw some conclusions from information available concerning the penetration capabilities of conventional radar. It is well known [Ramo 1965] that the attenuation constant of isotropic lossy materials usually increases with frequency. Hence, a radar operating at low frequencies will generally have better penetration properties than one operating at high frequencies.

The normal atmosphere has little effect on the sub-ionospheric propagation of UWB waves, which contain little or no energy above 10 GHz. Dense clouds of dust and heavy rain may produce substantial scattering and attenuation (up to 10 dB/km for rain). Snow is much less of a problem. None of these effects are significantly dispersive for ultra-short pulses.

Propagation of UWB waves through the ionosphere is another matter. Any components of such waves below 30 MHz may be assumed to be lost in transit through the ionosphere, which is no problem for UWB waves with spectra extending to 10 GHz or further. The problem is that ultra-short pulses may be greatly distorted depending on electron density, which varies with sunspot activity and will be difficult to take into account. These preliminary considerations suggest that conventional long-pulse narrow-band radar is likely to prove superior to UWB radar for applications requiring trans-ionospheric propagation. For example, detection of ICBMs by UWB radar will probably require locating the radar on a satellite.

3.1.3 Electromagnetic Response of Targets

Following the emission of the EM signal from the transmitting antenna and the propagation of that signal to the target, the response of the target to the incident EM signal must be considered. This process, which returns the signal to the radar receiving system, is the basis for any information to be obtained about the target. It is, therefore, one of the most crucial aspects of the entire radar process. In particular, if an advanced capability such as target identification is desired, this process must be understood in detail so that signals can be designed that result in sufficient information being returned from the target to allow it to be identified.

The determination of the EM response of targets can be understood through the discipline of EM scattering theory. For the case of impulse radar, this theory must provide a correct description of the EM scattering of "transient" signals from target structures. It is therefore a problem in time-domain EM theory as described in Section 3.1.1 and Appendix A.

Early work on the time-domain solution of scattering by perfect conductors was performed by Bennett [Bennett 1968]. A milestone paper on the representation of transient scattered fields is that of Marin [Marin 1973]. In this paper, he pointed out that the EM scattering from a large class of conducting scatterers is a *meromorphic* function of frequency. This mathematical result allowed the transient scattering for this class of problems to be represented as a sum of complex exponentials. This is an important consideration when target identification is being considered as described in the following section.

3.1.4 Target Identification

An area of research that is perhaps the most important in terms of achieving advanced radar capabilities is that of target identification and target imaging. Target identification and target imaging are very closely coupled with EM theory in the development of advanced capabilities based on impulse radar. There are a number

of approaches to target identification that need to be examined as to their applicability to impulse radar. One of the most important approaches, which is based on parametric system identification, is discussed in this section.

Parametric identification of transient systems is a concept that has only recently begun to appear in EM and applied-mathematics journals. The initial motivation for research in this area resulted from interest in transient EM scattering theory where the excitation is the electromagnetic pulse (EMP) produced by a nuclear weapon. This research is now driven primarily by the interest in the development of advanced radar capabilities such as target identification.

Parametric system identification is a subclass of system identification in which the information concerning the system is obtained in the form of a *parametric set*. Such a set, for example, might be the poles and zeros describing the system in the frequency domain. The theory of parametric system identification has been formalized by Ljung in a survey report on system identification [Ljung 1981] and in a joint paper with Glover [Ljung and Glover 1981] on a comparison of parametric with nonparametric methods. In addition, Ljung has contributed to the understanding of *bias* in the parameter estimates through investigation of stochastic noise models [Ljung 1978].

Signal representation consisting of fitting data with a complex exponential series dates back to the work of Prony [Prony 1795] whose method was resurrected by McDonough [McDonough 1963] and a number of workers in EM in the mid 1970's [Moffatt and Mains 1975, Van Blaricum and Mittra 1975, Miller 1981]. Subsequently, Dudley [Dudley 1979] showed that Prony's method is a special case of pole-zero parametric identification. The analysis and modeling of transient EM scattering in the established framework of system identification, particularly parametric system identification, utilizes signal-processing and system-modeling techniques based on advanced methods in applied mathematics. This approach is particularly valid for the modeling and analysis of UWB radar to determine the fundamental character-

istics and advanced capabilities it would have as compared to conventional radar techniques.

3.1.5 Target Imaging

The use of radar techniques to produce images of targets exhibits a dichotomy that portrays two vastly different stages of development. On one hand there is the production of 2-D images of extended areas, as is exemplified by the use of SAR for mapping purposes. Radars of this type are well developed and can produce high-resolution pictures by virtue of using signal bandwidth to achieve resolution in one dimension and using radar motion to achieve resolution in a second dimension. As discussed in Section 3.3.11, impulse radar appears to be capable of achieving this type of imaging as well as the more conventional sinusoidal-signal SAR.

The other aspect of radar imaging is that of producing the equivalent of 3-D images (that is, producing accurate 2-D projections of 3-D objects) of relatively small objects such as aircraft or missiles. This aspect of radar imaging is much less well developed and there are no existing operational radars that are capable of producing such images at long range. The reason for this failure is that excellent resolution in three dimensions is required, and the only way to achieve the requisite resolution in the third dimension with a monostatic radar is to use an antenna system with a very large aperture in that dimension.

Techniques for achieving true 3-D imaging with a multistatic radar have been proposed. These techniques are roughly the radar equivalent of the tomographic techniques used in X-ray technology to achieve 3-D images. One such technique is under investigation by Forrest Anderson. His technique employs the modified Radon transform to accomplish ellipsoidal backprojection of points in a 3-D space. This approach utilizes perhaps as many as ten or twelve antennas arranged in a circular configuration. The signal is transmitted from a single antenna in the center of the configuration and is received at all of the antennas in the circle. Although the

computational requirements are great, the technique appears to provide a feasible approach to identifying the number and relative locations of aircraft in a formation. Whether the same approach can also be used to identify the scattering regions on a single aircraft in three dimensions is still open to question. It is clear, however, that some form of UWB radar is essential to achieve the necessary range resolution.

Most of the 3-D monostatic radar techniques for imaging that have been demonstrated have been accomplished at short ranges, on the order of 1 km or less, and with an extremely narrow-beam antenna, which can only be obtained with practical antenna sizes by using millimeter waves (MMW). Several examples of such MMW radar-imaging systems are available in the classified literature. Much better cross-range resolution can be achieved using an infrared radar system, but neither this type of system nor the MMW system provides an all-weather capability.

3.2 Ultra-Wideband Technology

3.2.1 Impulse-Radar Transmitters

Impulse radars for short-range applications have been commercially available for several years. Ground-penetration radars are used by civil engineers and geologists for a variety of applications: locating pipes, reinforcement bars, voids, geological interfaces, hazardous wastes, lake and glacial ice profiles, etc. [Ulriksen 1982].

An impulse radar for the detection of intruders has been developed by ANRO Engineering Consultants of Lexington, Massachusetts. Pulse widths of a few nanoseconds are used to achieve detection ranges of 50–80 m. A detailed description of this system is available [Ross et al 1988].

Experimentation on impulse-radar transmitters using larger peak powers for longer-range applications has been conducted for many years by Paul Van Etten and his colleagues at Rome Air Development Center [Van Etten 1979]. Much of the RADC work has used spark gaps and transmission lines charged to high voltages

to generate nanosecond and subnanosecond pulses. Sequences of short pulses were generated in the RADC experiments by "frozen-wave" generators consisting of multiple spark gaps interconnected by transmission-line sections. Maximum ranges of a few kilometers were obtained. Further progress has waited on a practical means of obtaining pulses of higher peak power. However, the utility of impulse radar in target identification has been amply demonstrated by the RADC experiments.

Current emphasis of R&D in impulse radar is stimulated by the requirements for ranges of tens of kilometers in such applications as target identification. To produce high values of electric field intensity on targets at long range, extremely high rates of change of antenna current are required.

Solid-state devices capable of producing pulses with extremely short rise times and high peak power were developed at the Los Alamos National Laboratory in the early 1980s [Nunnally and Hammond 1983, Lee 1984]. Peak powers of many megawatts with subnanosecond rise times can be realized with these PCPS devices. The development of theoretical models of PCPS devices has also been completed [Iverson 1988]. Early consideration was given to the possibility of using these PCPS devices in radar applications to achieve improved range resolution [Cooper 1986].

The fall time of current pulses produced using PCPS devices is substantially longer than the rise time. The interval between pulses must be still longer to allow time for heat dissipation. The initial transient behavior of the current pulse is quadratic in time, so a reasonable model of the current pulse is $t^2 e^{-t/T}$. The rise time of the time derivative of such waveforms is less than half that of the waveform itself. If a 100-ps rise time in electric field intensity is required on the target, a current rise time of about 200 ps will suffice. Such short rise times can be realized with PCPS devices at high levels of peak power. Peak power levels of 100 MW delivered to a 25-Ω load were realized in PCPS experiments at Los Alamos for relatively long (200 ns) pulses. Exactly what levels of peak power can be achieved with rise times of 200 ps requires further experimentation.

A typical PCPS device is a block of semiconductor not more than a few centimeters in length. The cross-section is a rectangle, a fraction of a square centimeter in area. The experimental arrangement for some of the PCPS tests at Los Alamos is shown in Figure 3.1. The axis of the laser is in the direction of the thin dimension of the PCPS device. The circuit consists of a high-voltage pulse source driving the PCPS device and load in series. The resistance of the PCPS device is quite high until it is illuminated by the laser, when it drops suddenly to a small fraction of the load resistance. The timing of each pulse of load current is determined by the laser trigger, which can be accurately controlled so that pulse sequences relatively free of jitter can be produced conveniently.

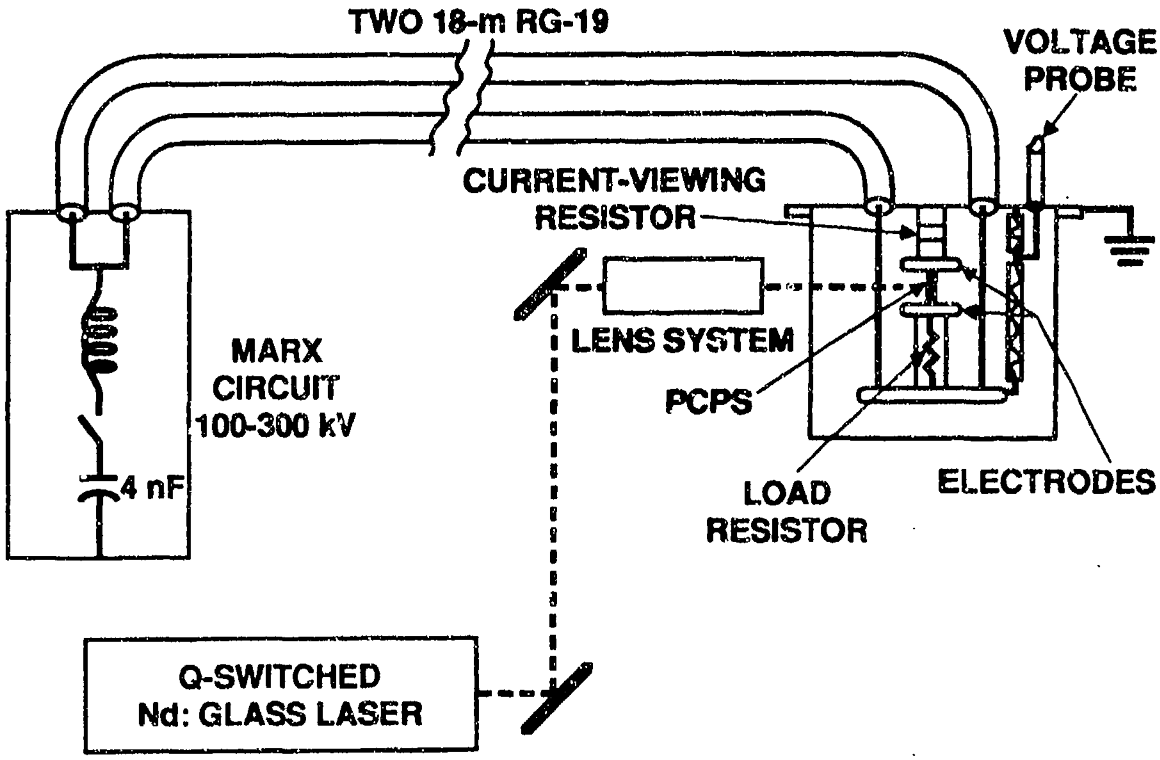

Figure 3.1: Experimental arrangement for PCPS tests

PCPS devices are efficient and can be scaled over wide ranges to meet requirements of a variety of impulse-radar applications. Thermal recovery occurs within tens of μs for typical PCPS designs, so that pulse repetition frequencies (PRF) of

tens of kHz can be sustained. Rates of change of antenna current of 10^{13} A/s are readily achievable. Scientists and engineers with extensive experience in impulse-radar R&D have indicated great interest in PCPS devices. Work is now under way to develop production PCPS devices by at least one commercial firm.

3.2.2 Antennas

The transmitting antenna is the "transducer" that couples the output from the high-power electrical-signal generator to the external environment of the target. The characteristics of the emitted EM signal resulting from this complex coupling process are critical to the capabilities and limitations of the entire remote-sensing radar process itself. Because of the UWB nature of the signal involved, the antenna problem is considerably different than for the usual narrow-band signals.

Conventional narrow-band antennas generally rely on sinusoidal resonance phenomena for their operation. For UWB signals, this resonance approach is not appropriate. A number of different approaches to coupling UWB signals from the electrical generator to the free-space environment are available, however.

One of these approaches is based on the idea of providing a broadband impedance transformation from the impedance of the electrical generator (often 50 Ω) to the impedance of free space (377 Ω). This is accomplished through a smoothly varying, tapered-transmission-line structure that flares out and "launches" the EM wave into free space. These structures often take the form of an open-sided horn antenna which is basically a tapered parallel-plate transmission line. The parallel-plate structure is tapered in both width and plate spacing in a number of possible ways such as linear or exponential tapers.

Another approach is to build an antenna structure that is comprised of a number of narrowband elements that completely cover the entire bandwidth of the signal. These structures are often based on the log-periodic Yagi idea. A third approach is based on the idea of an antenna structure that emits an EM signal produced by

an excitation resembling a time-varying current sheet.

Time-domain electromagnetics is key to impulse-radar R&D as it includes the analysis and measurement of the emission, propagation, reflection and reception of *transient* electromagnetic waves. The study of transmitting and receiving antennas for impulse radar has to start from basic principles, because the standard antenna theory is limited to the special case of sinusoidal excitation. The engineer with extensive experience in classical narrow-band radar systems, who is starting to work on impulse radar, is advised to heed Mr. Dooley's aphorism.

> It was not the things we didn't know that hurt us.
> It was all the things we knew for sure that turned out to be wrong.

The differences between the performance of an antenna or an antenna array excited by extremely short transients and that produced by steady-state sinusoidal excitation are many and large. Antenna patterns for transient excitations do not have the deep nulls and sidelobes characteristic of sinusoidal excitations. A similar statement can be made for the variation of target RCS with aspect angle. As a signal-processing operator, the transmitting antenna may be regarded as a differentiator and the receiving antenna as a scalar multiplier. The opposite interpretation is also possible, because t-differentiation and scalar multiplication commute.

Several examples of the significant differences between transient and steady-state excitation of antennas are shown in Appendix B, where an array antenna in an impulse-radar application is considered.

3.2.3 Receivers

This section outlines several important aspects of the hardware design of receivers for impulse radar. Section 3.2.4 discusses the actual processing requirements in the receiver in more detail. The particular aspects considered are the isolation of the receiver from the transmitter, the receiver input circuit, the signal detection processor, and post-detection processing.

A critical problem in the design of the receiver is isolating the receiver input from the high-power pulse produced by the transmitter. Because of the large bandwidth of the transmitted signal and its extremely large peak power, it is unlikely that the isolators and circulators used in conventional radar for this purpose will perform satisfactorily in impulse radar. This suggests that it may be necessary to use separate transmitting and receiving antennas. However, even with separate antennas it is necessary to provide additional protection for the receiver because the distance between them is likely to be small and shielding has only a limited effectiveness. Two isolation techniques appear possible. One is the use of signal cancellation at the receiver input by providing a reversed signal to cancel the leakage signal. For a fixed radar installation this may be possible, although it might be very difficult with a scanning antenna. A more direct approach is to provide fast-acting switches that short-circuit the receiver input when the transmitter pulse is on, using low-power devices operated under the control of the transmitter. Two possibilities are PIN diodes or PCPS devices, the latter being more convenient if the transmitter uses PCPS devices to generate the antenna-current pulses.

When signal detectability is a primary concern, the major problem with the receiver input circuit is that of obtaining adequate bandwidth without introducing an excessive amount of noise. This implies that careful attention must be given to the design of suitable low-noise amplifiers covering a frequency range of perhaps 10 MHz to 10 GHz. It is possible that cooled input circuits may be necessary in some cases. When there is ample signal power, as would be the case in many target-identification applications, the effect of receiver noise will be less severe.

Two other complications arise in connection with the receiver input circuits. One of these pertains to the antenna noise that arises in addition to the noise in the input circuit itself. Antenna noise results, in part, from cosmic radiation and can be quite large at low frequencies. For example, an antenna pointing toward the sky will have a noise temperature in excess of 3000 K at frequencies below 100 MHz. This

large noise at low frequencies may establish a limit on the lowest frequency that can be employed usefully by impulse radar. The second complication in the input circuit arises if notch filters are necessary to reduce interference from narrow-band signal sources. Not only is the design of the input circuit made more difficult, but the additional losses decrease the signal energy and increase the noise.

The form of signal-detection processor depends strongly upon the application for which impulse radar is intended. Various possibilities for detection processors and the circumstances in which they might be used are discussed in more detail in Section 3.2.4. The three basic types of signal-detection processors mentioned are the energy detector, the matched filter, and the cross-correlator. The implementation of such processors is discussed briefly here.

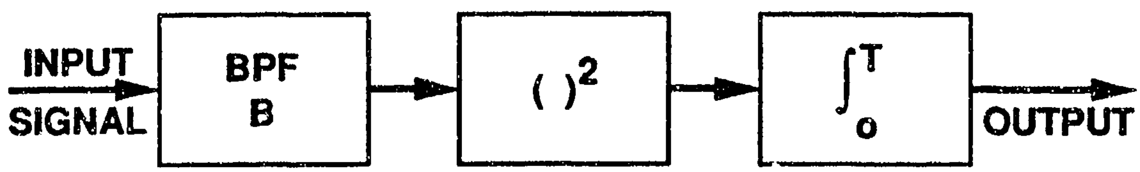

Figure 3.2: An energy detector for radar

A block diagram of the typical energy detector is shown in Figure 3.2. The square-law device can be almost any nonlinear device if it is operated at a low signal level. The integrator may be replaced by a low-pass filter with a bandwidth equal to the reciprocal of the desired integration time. As indicated elsewhere, the integration time should be at least as large as the round-trip propagation time over the extent of the target. This makes it possible to include all of the signal energy from the target in each detection operation, but it does destroy the range resolution that would otherwise be available from the large signal bandwidth. This type of

detector is useful when target detection is the primary application of the radar.

The second form of signal-detection processor is the matched filter. The matched filter is one whose impulse response is the time-reversed replica of the signal returned from a single reflecting point. The exact implementation of such a filter is probably not possible, but approximations can be constructed. One possibility for such an approximation is the use of a channelized input. This type of receiver input circuit utilizes parallel filters, each having a bandwidth that is only a fraction of the total bandwidth, but centered at different frequencies so that the total parallel combination of filters spans the entire desired bandwidth. The gain of each parallel filter can be adjusted to be proportional to the magnitude of the transfer function of the true matched filter in that portion of the spectrum. Not only does this approach approximate the transfer function of the matched filter, but it also provides a useful means for excising portions of the spectrum to exclude narrow-band interfering signals. A careful analysis of the requirements on such parallel filters has not been done, but it is likely that very careful control of the phase characteristics of the filters is necessary to achieve an adequate approximation to the desired matched filter.

Although the matched filter provides the maximum output SNR, this maximum pertains to each scattering region on the target and not to the total signal returned from the target. This is the appropriate response for target identification, but does not utilize all of the returned signal energy for detecting the presence of the target. Thus, this type of detector is most useful after the target has been detected and is close enough for a more detailed examination.

The third type of signal detection processor is the cross-correlator in which a replica of the returned signal from a single scattering region is generated in the receiver, with a delay corresponding to the round-trip propagation time to the target. The replica multiplies the received signal and the product is then filtered in an appropriate low-pass filter. A block diagram of this type of detector is shown in

Figure 3.3. The maximum output SNR of the cross-correlator is identical to that of the ideal matched filter. Because the form of the received signal from a single scattering region is known, the reference signal can be generated in the receiver with good accuracy. From this standpoint, the cross-correlator is probably a better implementation of the signal-detection processor than the matched filter, which can be implemented only approximately. However, in order to observe returns from a number of ranges at the same time, a large number of cross-correlators (possibly several thousand) need to be implemented and this poses a substantial hardware-implementation problem. For example, to observe all possible scattering points on a target having a range extent of 20 m with an impulse radar having a range resolution of 2 cm requires 1000 cross-correlators. In addition, bulk delay to place all of the cross-correlators on the target is also necessary.

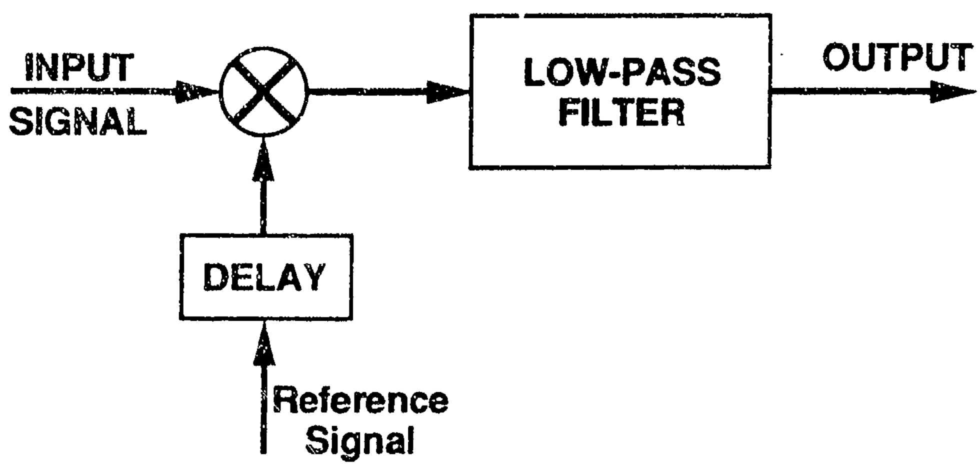

Figure 3.3: The cross-correlator detector

It may turn out that a hybrid signal-detection processor will provide the best solution to the target-detection problem. One possibility for this is to use an energy

detector, with the appropriate integration time, at the output of the matched filter, or to sum the outputs of the cross-correlators and put this sum into an energy detector. Whether this combined operation will provide a better probability of detection than the energy detector alone is a matter for further study. In any event, this approach has the advantage of retaining the excellent range resolution of the matched filter or cross-correlator while utilizing all of the energy from the target for detection purposes.

The form of post-detection processing required is also critically dependent upon the application for which impulse radar is intended. Post-detection processing will almost certainly have to be digital when target identification is the major concern. This requires that the peak outputs from the matched filter or the cross-correlators, and the times at which these peaks occur, must be digitized and stored so that identification algorithms can be implemented. Although complete sampling of the outputs of the matched filter or the cross-correlators appears to be difficult to achieve, there seems to be no practical difficulty in accomplishing this digitization for the peak outputs only. When the objective is target detection only, and range resolution is not an issue, the appropriate output must be compared with a threshold and quantized whenever the threshold is exceeded. Because of the relatively poor range resolution that occurs in the case of target detection only, this operation appears to be easy to accomplish.

3.2.4 Signal Processing

There are two major aspects of signal analysis that need to be considered in connection with the development of a viable impulse radar. The first of these is the design of optimum antenna-current pulse shapes and optimum groups of pulses. This aspect is discussed in more detail in Section 3.4.1. The second aspect is to determine the modifications in signal shape that take place as a function of the antenna transient response, target transient response, and the receiver input circuit

characteristics. The target transient response is addressed in more detail in Section 4.4. Very little has be done so far in determining the antenna transient response or in examining the transient performance of the receiver input circuit. An analytical program must be initiated to explore these aspects of system performance in detail before embarking on any effort to design an impulse radar. In addition, the analyses aimed at determining the optimum pulse shape and the transient response of typical targets must be carried further.

The ultimate purpose of the radar receiver is to process whatever signal is returned from the target to determine as much information about the target as possible. This information may range from a simple decision concerning target presence to a detailed picture of the various scattering regions on the target. Hence, many different signal-processing methods must be analyzed in order to determine those that are best for each application. The possible signal-processing methods include the energy detector for target detection, the matched filter or the cross-correlator for identifying individual scattering regions on the target, the use of parallel input channels to approximate the matched filter, and the use of composite matched filters to identify known clusters of scattering points to enhance detectability.

It may turn out that it is desirable to use a combination of processing methods in the typical impulse-radar receiver in order to achieve the benefits of the extremely good range resolution without sacrificing detectability. One possibility is to use an energy detector with sufficient integration time to include all returns from the target and also use a matched filter to achieve the resolution necessary to separate the individual scattering regions. A more effective, but more complex, solution is to use a large number of cross-correlators, adjusted to respond to potential returns in adjacent range cells, and put the sum of their outputs into an energy detector. A third possibility is to use an energy detector with sufficient integration time at the output of a single matched filter. All of these concepts should be analyzed in sufficient detail to establish their relative merits for accomplishing both signal

detection and good range resolution.

Another important aspect of the processing requirements in the receiver depends upon whether the application intended for impulse radar involves the nearly simultaneous processing of returns from multiple targets. This situation arises, for example, in a track-while-scan application or in attempting to discriminate between decoys and warheads during a missile attack. Although the processing requirements for each target are essentially the same as outlined above, the multiplicity of targets greatly complicates the situation. This type of application undoubtedly calls for at least a portion of the processing to be done digitally.

Although the initial design of signal-processing methods will probably involve analog processing, as noted above, it is desirable to consider the feasibility of using digital techniques in future processors. Because of the extremely short duration of the signal pulses, this is a challenging problem. It is likely, however, that the methods employed in wideband oscilloscopes can be adapted to accomplish the desired processing tasks.

It has often been stated that the impulse-radar signal contains very little Doppler information, and this statement is frequently cited as one of the disadvantages of impulse radar. This conclusion is undoubtedly true so far as extraction of information from a single received pulse is concerned. However, in most applications, and certainly in the case of target identification, more than one pulse is received. In such cases the time interval over which the received signal is observed is such that it is theoretically possible to extract the Doppler information that is actually present in the received signal. This possibility is addressed in the following paragraphs.

The usual concepts of extracting target range-rate information from the Doppler shift of the received signal frequency are based on the assumption that a sinusoidal waveform is employed. In the case of impulse radar there is no such sinusoidal wave so that the usual concept of a frequency shift is not applicable. More fundamentally, the effect of target motion is not that of a frequency shift, but the time contraction

contraction or expansion of the received signal. Interpreting such a change in the time scale as a frequency shift is an approximation that is valid only for relatively narrowband signals.

A preliminary time-domain analysis of the received impulse-radar signal from a moving target reveals that the information regarding target range-rate is indeed contained in the sequence of returned pulses. The present analysis has assumed the use of cross-correlator detection, but it is likely that similar results can be obtained from other detectors. The analysis has not yet been carried far enough to indicate the actual implementation procedures that should be used to extract the desired range-rate information, but it seems clear that the necessary information is present in the received signal. As in conventional radar, better estimates of target range-rate are achieved by processing the received signal over a longer time interval.

3.3 Potential Capabilities and Applications

A vital concern with the development of impulse radar is whether there are applications that cannot be achieved with conventional pulse radar, or cannot be achieved as easily. Hence, the purpose of this section is to propose certain applications for which impulse radar appears potentially superior. One cannot be certain about the viability of any the following potential applications without a great deal of additional analysis and experimentation. All that can be done here is to present some arguments that suggest that these applications have potential.

3.3.1 Target Identification

Target identification is perhaps the single most important advanced capability of any radar system, and is of great interest to a number of organizations. Target identification provides the most complete information regarding a target short of producing an actual image of the target. Some of the theoretical considerations

concerning target identification and some proposed techniques are addressed in Section 3.1.4. The purpose of this section is to indicate the extent to which impulse radar may be able to fulfill these theoretical requirements.

Perhaps the most important requirement for any method of target identification is the use of a radar that has adequate range resolution to be able to resolve individual scattering regions on the target. Impulse radar meets this requirement extremely well. Not only does this make possible the determination of target extent in range, but if the target is rotating, the size in other dimensions can be determined as well. If a nonrotating target is observed over a long enough interval that its aspect with respect to the radar changes appreciably, the concepts of differential geometry can be used to determine something about the curvature of the target surface. Range resolution of 1 cm or so, which is readily achievable with impulse radar, makes this technique a sensitive indicator of certain aspects of target shape.

Another approach to target identification is that of representing targets as a sum of complex exponentials. If a catalog of such complex exponentials at various aspect angles were available for each target of interest, then the use of Prony's method on the received signal would provide a systematic approach to target identification.

Two other aspects of target identification involve the possibility of detecting resonances in the target-return signal and the detection of return-signal modulation by the target such as might be produced by jet-engine rotors. It appears quite likely that impulse radar, with its extremely large bandwidth, can do a better job of detecting target resonances than conventional radar. This statement is particularly true if the resonances occur at frequencies below the usual radar bands. The set of frequencies at which such resonances occur is probably unique to each type of target. No analysis has yet been performed to indicate how such resonances show up in the received signal from impulse radar, but experience suggests that a spectral analysis of a sequence of returned pulses should reveal this type of information.

Jet-engine modulation is conventionally observed by Doppler techniques. It is

not yet clear that such modulation can be observed over a sequence of pulses from impulse radar, but as noted in Section 3.2.4, a preliminary analysis suggests that this may be possible.

Because of the importance of target identification to the Department of Defense (DoD), and because impulse radar appears to have some unique capability in this respect, a more complete analysis of this potential capability is *urgently* needed.

3.3.2 Low-Observable Target Detection

Detection of Stealth Targets

One of the suggested applications of impulse radar is the possibility of more easily detecting LO targets having a small RCS by virtue of the use of a radar-absorbing material such as ferrites. These materials are alleged to function successfully over only a relatively narrow frequency band [Harmuth 1983a, Harmuth 1985]. In fact, Harmuth suggests that ferrite materials can reduce radar signal reflections by 20 dB over a relative bandwidth of only about 0.125. It appears, therefore, that an impulse-radar signal having a relative bandwidth on the order of unity would have a significant portion of its energy reflected by the ferrite material and its metallic backing, and thus make this type of LO target more readily detectable.

On the other hand, it has also been suggested [Thornton 1986] that this problem can be ameliorated by using ferrites in conjunction with other unspecified materials and with an appropriate spatial distribution. There does not appear to be any data in the open literature that supports this claim. In fact, the book by Knott et al [Knott 1985] has an entire chapter devoted to radar-absorbing materials and suggests that even with four layers of hexagonal ferrite, the RCS reduction can be as great as 20 dB over a relative bandwidth of only about 0.17. One can conclude, therefore, that a thorough investigation of the classified literature is necessary before one can assert that the use of UWB signals does or does not make this type of LO target more detectable.

Detection of Shape-Controlled Low-Observable Targets

Another approach to designing LO targets is to control the shape of the target by eliminating flat surfaces, sharp edges, and external features that might be resonant in any of the commonly used radar bands. However, if the radar signal covers a very wide range of frequencies, as does the impulse-radar signal, this approach becomes much more difficult to implement.

Consider, for example, an aircraft that must carry communications antennas. Even if the antennas are conformal to the surface, they must be nearly resonant at their operating frequencies to do an effective job of both transmitting and receiving. Many communication frequencies are on the order of a few hundred MHz, well below the usual radar bands. However, the spectral density of impulse radar is almost directly proportional to frequency from zero frequency up to near the maximum spectral density (see Appendix B for example). Thus, there is a significant amount of signal energy throughout the communications bands, and these antennas could easily reflect more energy than the rest of the aircraft. It seems likely that any type of vehicle will have some features that are resonant at some frequency within the bandwidth of the impulse-radar signal, even if they have been carefully designed to avoid such resonances in the conventional radar bands.

Although the above conclusions appear plausible, much work is required to determine the time-domain response of such objects rather than reliance on frequency-domain concepts. Even so, on the basis of what is currently known about impulse radar, the conclusion that LO targets are more easily detected by impulse radar is eminently reasonable.

3.3.3 Target Imaging

The term "radar-target imaging" suggests that the radar is capable of producing a 2-D outline or even a 3-D picture of the target. An outstanding example of this type of image is the high-quality ground map that can be produced by SAR. Such

maps are possible because range resolution can be used to provide the resolution in one dimension, while the synthetic-aperture processing provides the resolution in the other dimension.

A long-time dream of radar practitioners is that of obtaining similar high-quality images of small 3-D objects such as aircraft, missiles, tanks, etc. That such a dream has yet to be fulfilled in any real sense results from the limitation to resolution in two dimensions only, unless an extremely large antenna structure is used. In its normal monostatic mode of operation, impulse radar does not provide any solution to this problem. However, as noted in Section 3.1.5, multistatic operation may provide a solution, and research related to this possibility is already under way.

It is reasonable to question whether impulse radar provides any advantage over conventional radar in a multistatic mode of operation. Preliminary consideration of this problem suggests at least two possible advantages that can be obtained from the use of impulse radar. It is assumed here that the transmitted signal comes from a single antenna and that the signal returned from the target is received at a number of receiving sites. Since the range extent of each pulse is essentially the same as the range resolution, a group of pulses separated in time only by an amount somewhat greater than that equivalent to the target size can be transmitted. Furthermore, successive pulses in the group can be modified to place the maximum energy at different places in the frequency spectrum so that the possibility of exciting unique target resonances is enhanced. This does not appear to be possible with conventional spread-spectrum radar because each pulse will itself have a duration longer than the equivalent target extent, and will not have as large a bandwidth as the impulse-radar signal.

The second possible advantage that impulse radar may offer in the multistatic mode of target imaging is more precise timing of the received pulses. This is important in multistatic operation in order to correctly assign each return pulse in each receiver to the proper scattering source. The more precise timing is a con-

sequence of the greater bandwidth of impulse radar as compared to conventional spread-spectrum radar.

3.3.4 Penetration Radar

The problem with conventional radar operating at low frequencies is that of obtaining sufficient bandwidth in the signal to achieve the desired range resolution. Impulse radar does not suffer from this problem, because the radiated signal can have a relative bandwidth approaching unity. Indeed, a number of ground-penetration radars operating essentially on impulse-radar principles are known to exist [Harmuth 1983b].

The use of impulse radar for ground penetration to detect tunnels, bunkers, mines, etc., has been widely proposed and appears to have considerable merit. A related application is the penetration of foliage to detect manmade objects that would otherwise be hidden from view. This application is of particular concern in locating missiles, launchers, tanks, trucks, etc., which can be effectively hidden from conventional radar and infrared sensors by both foliage and camouflage. Recent work by John McCorkle at Harry Diamond Laboratory on SAR in foliage penetration indicates some advantages in using impulse-radar techniques.

The possibility of using radar to penetrate buildings to identify the nature of contents may be valuable in intelligence applications. The optimum frequency for accomplishing such building penetration is strongly dependent on the type of construction used in the building. If the walls and roofs are pre-stressed concrete or wood, then low frequencies are probably best. If the walls and ceiling are steel reinforced concrete, somewhat higher frequencies are likely to be better. If the walls are metal, then penetration is possible only through openings such as windows and doors. Whether impulse radar is any better than conventional radar for building penetration is a matter of conjecture at this point. However, it seems likely that the very wide frequency range of impulse radar may be useful in providing initial

information as to the optimum frequencies that a narrow-band radar should use for this application.

Another potential application pertains to the ability of impulse radar to penetrate plasma regions caused by nuclear explosions, rocket exhaust, re-entry wakes, etc. Such plasma regions typically become more transparent as the incident frequency increases. Because the impulse-radar signal contains such a large range of frequencies, the higher end of this spectrum may be able to provide more detailed information about targets engulfed in such plasma regions than would a conventional radar. Furthermore, the fact that lower frequencies are also present in the impulse-radar signal provides a greater ability to penetrate the atmosphere and provide better detection of targets that are not in plasmas. Thus, the same impulse radar may be able to perform a combination of tasks that would otherwise require two conventional radars.

3.3.5 Short-Range Radars

A problem with conventional radar is that of observing targets at very short ranges. Even if adequate power control is available, the signals returning from short ranges often arrive back at the receiver while the transmitted signal pulse is still on. This problem is particularly severe if spread-spectrum techniques are used to improve the range resolution, and an excellent range resolution is often a requirement of short-range radars. Impulse radar, on the other hand, uses a very short pulse and has a minimum range (assuming adequate power control) that is essentially the same as the range resolution.

To illustrate this problem, suppose that a spread-spectrum radar uses a pseudorandom sequence that is 511 chips long with a chip duration of 1 ns. This provides a range resolution of about 15 cm with range sidelobes that are down by about 13.5 dB. The pulse duration is 511 ns, which provides a minimum range of about 76 m, hardly adequate for many of the applications mentioned below. In contrast to this,

an impulse radar with a pulse duration of 200 ps has both a minimum range and a range resolution of about 3 cm and no range sidelobes. This is indeed a dramatic improvement in performance that can be achieved by impulse radar.

Applications that require the use of a short-range radar combined with excellent range resolution include spacecraft docking, missile fuzing, intrusion detection, vehicle-collision avoidance, and station keeping in aircraft formations. In all of these applications, impulse radar is a viable candidate.

3.3.6 Target/Decoy Discrimination

An important radar application in connection with a missile attack is that of discriminating between actual warheads and decoys. In general, decoys are designed to have a ballistic coefficient and a conventional radar signature that closely approximates that of a warhead although the decoys are physically much smaller. Conventional long-range radars used to track such objects usually do not have sufficient range resolution to discriminate well between the decoys and warheads.

Impulse radar does have adequate range resolution to discriminate physical size when the decoys are dispersed separately. It is not so clear that such discrimination is equally possible when decoys are tethered together to create an object more nearly the same physical size as the warhead. It seems likely that, even in this case, significant differences in the returns will lead to possible discrimination.

A possible problem in this application is that of obtaining sufficient impulse power to achieve this objective at the ranges of interest. As noted elsewhere in this report, the detectability of any target depends primarily on the energy of the returned signal and not the peak power. When the pulse duration is short, as it must be in impulse radar to obtain the desired range resolution, the necessary peak powers may be in excess of limitations imposed by dielectric breakdown at the transmitter. On the other hand, much larger potential differences are required to damage insulation as pulse durations are reduced to the ultra-short intervals

proposed for impulse radars.

3.3.7 Intrusion Detection

The application considered here is that of being able to detect the intrusion of personnel into a secure area such as that surrounding a temporary military installation. Although infrared and ultrasonic devices are commonly used for this application, radar may have an advantage in all-weather capability. Radars used for this purpose may be low-power short-range devices with a range resolution on the order of a few feet and good Doppler resolution. An important consideration in the design of such intrusion-detection systems is that of minimizing false alarms caused by dogs, squirrels, or other small animals.

Although impulse radar is not yet considered to have a Doppler capability, it may still be useful in short-range applications by indicating motion as a consequence of range changes from observation to observation. The excellent range resolution should make this approach feasible, as well as provide a better opportunity to distinguish between humans and animals.

Another mode of operation that might be feasible for this application is to use two or more impulse radars in widely separated positions, each with a very broad beamwidth and no angular scan. Target positions could be accurately determined by triangulating the range-only measurements from each radar. This approach has the advantage of providing constant surveillance of an entire area rather than the periodic surveillance associated with a scanning radar. The disadvantage is the possibility of "ghost" targets that result from incorrect association of returns.

3.3.8 Detection of Sea-Skimming Missiles

The sea-skimming missile tends to be relatively small and to operate only a few feet above the surface of the ocean. As a result of their small RCS and the existence of a large amount of sea clutter, such missiles are very hard to detect. There is

a possibility, not yet evaluated in any quantitative sense, that the excellent range resolution of impulse radar, combined with the absence of any range sidelobes such as are typical of spread-spectrum radars, could provide better detectability for this type of target. Because of the short reaction time necessary for successful detection of sea skimmers, the fact that no Doppler processing is necessary may also be an advantage.

3.3.9 Detection of Cruise Missiles

Another important defense problem is that of detecting cruise missiles. Some of these weapons fly at low altitudes to be below the radar horizon for surface-based radars and to be obscured by ground (or sea) clutter from most airborne radars. Furthermore, even without the use of radar-absorbing materials, cruise missiles have a considerably smaller RCS than a typical aircraft, and if it also has a stealth surface, it becomes extremely difficult to detect.

As noted in Section 3.3.2, impulse radar may have a significant advantage in detecting LO targets because of its large bandwidth. This advantage, if real, would be equally useful in aiding the detection of cruise missiles. Furthermore, the absence of range sidelobes and angle sidelobes (Appendix B) may provide an improved signal-to-clutter ratio for an airborne platform. Consider an impulse radar having a range resolution of 0.1 m and employing an antenna with a beamwidth of 1 degree. If the RCS of the surface per unit area is −25 dB at a range of 100 km, the equivalent clutter cross-section is about 0.55 m^2 in each range cell for impulse radar. Assuming that each scattering region on the cruise missile has an RCS on the order of 0.1 m^2, the signal-to-clutter ratio in each range cell is about −7.4 dB on a single-pulse basis. Approximately 100 pulses would have to be integrated to obtain a probability of detection on the order of 0.9.

Consider next a corresponding conventional spread-spectrum radar with a range resolution of 6 m (just enough to encompass the cruise missile), and with range

sidelobes down by 30 dB (an optimistic value). In this situation the radar would produce an equivalent clutter cross-section of about 100 m^2. If the conventional RCS of the cruise missile is 1 m^2, and the clutter RCS is 1 m^2, the resulting signal-to-clutter ratio in each range cell is about −20 dB. In this case, about 2000 pulses would have to be integrated to achieve the same probability of detection.

3.3.10 Radar-Cross-Section Diagnostics

The above discussion of the ability of impulse radar to detect LO targets suggests another application of impulse radar in the development of such LO vehicles. The extremely good range resolution of such a radar should make it possible to identify the location of flare spots and other major scattering surfaces by observing accurate scale models of the devices. An impulse radar with a bandwidth of 10 GHz has a range resolution of about 1.5 cm. Thus, even on the one-fifth scale models used in such fuze-testing facilities as the Encounter-Simulation Laboratory of the Naval Weapons Center, the individual scattering regions should be readily identified.

3.3.11 Synthetic-Aperture Radar

SAR relies on motion of either the radar or the target to create a signal that appears to come from an antenna aperture much larger than the actual physical aperture. With appropriate signal processing, this results in achieving a cross-range resolution (i.e., parallel to the direction of motion) that can be one-half the physical aperture dimension. The conventional SAR employs a spread-spectrum signal having a bandwidth on the order of tens of MHz to achieve a down-range resolution (i.e., perpendicular to the direction of motion) that is the same order of magnitude as the cross-range resolution. The result is a radar that is capable of providing maps of the ground or images of a target.

The first operation that must be performed by the typical SAR receiver is that of despreading the spread-spectrum signal so that the Doppler information can

be extracted. For impulse radar this operation is unnecessary because the signal spectrum has not been spread. On the other hand, each pulse of the impulse radar carries essentially no Doppler information because of its short duration. To compensate for this short duration is the fact that returns from different angles arrive at the receiver at different times and may be extracted on the basis of time rather than Doppler frequency. The exact nature of the required processing has not been studied in any depth, but it appears likely that an appropriate method of combining data from the multitude of range cells would again lead to a SAR-type image. It also appears likely that the required processing may be less difficult than that required for the conventional SAR, although this is yet to be established.

Another potential advantage of using impulse radar for SAR operation is that the bandwidth necessary for a desired range resolution can be achieved at lower frequencies. As noted above, this enhances foliage penetration and increases the likelihood that the SAR can detect and identify targets that are normally hidden by foliage.

Offsetting the possible advantages of impulse radar for SAR applications is the need for extremely good clock stability. A rough calculation for a SAR system having a range resolution of 0.3 m at a range of 100 km suggests that a short-term clock stability on the order of 4×10^{-11} may be necessary to achieve the desired performance.

3.3.12 Low-Angle Radar

Another application suggested for a land-based impulse radar is that of detecting and identifying targets that are only a few degrees above the horizon. Most conventional radars have great difficulty with low elevation angles because of the large amount of ground clutter surrounding the range to the target. The effects of such clutter can be reduced by improving the range resolution of the radar, because the amount of clutter power that is in the range cell containing the target is reduced.

The even better resolution of impulse radar should improve this situation further. However, a more detailed consideration of this problem suggests that the law of diminishing returns operates here. As the range resolution is made smaller than the target, the target return gets smaller at about the same rate as the clutter power. A much more detailed analysis is necessary before it can be concluded that the impulse radar has a viable role in low-angle applications.

3.3.13 Low Probability of Intercept

The LPI capability of any radar is dependent upon the capability that one assumes for the intercept receiver. This is also true for impulse radar. First, we must assume that at reasonable ranges the R^2 advantage that the intercept receiver enjoys with respect to the radar applies in all cases of interest. Hence, even if the intercept receiver employs energy detection (as it must in almost all cases), it will always detect the radar signal if it is observing in the right direction at the right time. The clue to any potential LPI advantage of the impulse radar must lie in its extremely low duty factor, which may be on the order of 10^{-7} to 10^{-9}, and its extremely large bandwidth, which may be as large as 10 GHz. The analytical basis for an LPI advantage is discussed in more detail in Section 3.4.4.

3.3.14 Low Probability of Exploitation

Impulse radar may provide a means of avoiding exploitation without requiring multimode operation. The basis for this conclusion is discussed in Section 3.4.4.

3.3.15 Nonapplications

Several applications of more conventional radar do not appear to be feasible for impulse radar. Although impulse radar may have an advantage in the detection of LO targets, it does not appear to be particularly useful for early warning applications.

Conventional radars used for early warning use a very low pulse repetition rate with a great deal of radiated signal energy in each pulse. This large signal energy is essential to accomplish detection of aircraft or missile targets at ranges up to several thousand miles. Obtaining an equal amount of energy in a short intense pulse does not appear possible with present technology. However, as the technology of high-power pulse generation advances, this conclusion may be changed, particularly if generation of closely spaced high-power pulses becomes feasible.

A frequently expressed opinion is that the limit on the peak power that can be generated in a single pulse is set by limits on electrical breakdown. However, electrical breakdown of air or any other material requires the electrical field to be present for a non-zero interval of time. It has been demonstrated that pulses that are shorter than this minimum time ("sneak-through") will not cause the material to break down. Thus, the limit imposed by electrical breakdown may be higher than that expected from long-pulse measurements.

Another nonapplication for impulse radar appears to be over-the-horizon (OTH) radar. Operation of such a radar requires the use of frequencies below 30 MHz because reflection from the ionosphere is required. Although pulses that concentrate the energy at frequencies below 30 MHz are certainly possible, such pulses will have a duration sufficiently long that sneak-through cannot occur. Thus, there will be a limitation on peak power due to electrical breakdown and a corresponding limit on the available energy per pulse. It appears likely that the limit on pulse energy is such that OTH operation is not feasible. Furthermore, even if sufficient energy could be achieved, the range resolution is such that there would be smaller returns from targets of interest. This loss would be partially compensated by a reduction in clutter energy, but it is unlikely to be a sufficient reduction because of the diffuse nature of reflections from the ionosphere.

Although measurement of target velocity appears to be feasible with impulse radar, such measurements are not likely to be as accurate as measurements made

with a sinusoidal-signal radar with the same amount of returned signal energy. This conclusion has not been verified by analysis as yet, so it may be incorrect. However, if it is correct, then any application of radar in which velocity measurement is the primary objective may be better carried out by conventional sinusoidal radar. An application that comes to mind is that of police radar used to observe speeders. However, to offset this possible disadvantage is the fact that conventional police-radar warning devices would probably not detect the impulse-radar signal.

As noted earlier in this report, propagation through the ionosphere would result in substantial distortion of impulse-radar signals. Applications requiring trans-ionospheric propagation will probably be better served by conventional radar.

It now appears that suitable angular directivity for impulse-radar antennas can be achieved only by the use of arrays. Because arrays are likely to be more complex and more costly than the parabolic dish antennas used so often for conventional radar, it may uneconomical to employ impulse radars where their unique capabilities are not really required, even if somewhat better operation can be achieved with impulse radar. Similarly, any application requiring the use of s single antenna may not be feasible for impulse radar because of deficiencies in existing isolators and circulators. This may be a temporary limitation, however, as the technology of such devices becomes more advanced.

3.4 System Design and Analysis

Because impulse radar is significantly different from conventional radar, many new aspects should be analyzed before a viable system design can be achieved. This section outlines the nature of some of these aspects and suggests the approaches that seem most reasonable. In almost all cases the nature of the required analysis strongly depends on the application for which impulse radar is employed. However, it is not our intent to provide quantitative results on any of these topics, but simply

to outline some of the analyses that ought to be done.

3.4.1 Optimum Signal Design

Unlike conventional sinusoidal-signal radars, it is necessary to distinguish between the signal waveform at the transmitting antenna and the form of the radiated EM field. Harmuth [Harmuth 1983b] has shown that the far-zone electric field is very nearly proportional to the time derivative of the transmitting antenna current. Consequently, the bandwidth of the energy-density spectrum of the radiated signal depends primarily on the rise time and fall time of the antenna current pulse and is almost independent of the pulse duration.

Also, Harmuth has shown that some constraints on the form of the antenna current must exist in any physical system. In particular, if the antenna current is to be zero prior to the pulse, then both the antenna current and the derivative of the antenna current must be initially zero.

The actual shape of the antenna-current pulse is determined primarily by the mechanism used to generate this pulse and may be difficult to control. It is assumed here, however, that some control can be exercised over the rise time and fall time of the antenna current pulse, and that the timing of antenna-current pulses can be precisely controlled.

Avoiding range ambiguities in the intended application requires that the repetition interval between pulses or pulse groups be greater than the round-trip propagation times for the expected ranges. Apart from this, however, there is considerable flexibility in designing pulse groups that have special properties. For example, one can design a pulse group with variable spacings that has a "single-coincidence" property. That is, for any relative time shift between the transmitted signal and the received signal, other than zero, at most one pair of pulses coincide. Such a pulse group has a correlation function with the low correlation sidelobes necessary for good range resolution but provides increased signal energy for better detectabil-

ity. Such pulse groups may well be optimum for those applications of impulse radar, such as identification of LO targets, in which both excellent range resolution and detection at large ranges are important.

Additional flexibility in signal design exists if the antenna current rise and fall times can be controlled. This type of control makes it possible to select the range of frequencies in which the maximum energy density occurs. Thus, if the application involves penetration of a conducting medium, increasing the rise and fall times of the current pulse will put more radiated signal energy at lower frequencies and improve the penetration capabilities. This flexibility also has implications for EM compatibility, which is discussed in Section 3.4.5.

A third aspect of optimum signal design has to do with power control. The LPI capability of a radar is enhanced if the radiated signal energy is no greater than that needed for detection of the desired target at the desired range. This is particularly true at short ranges where the range advantage of an intercept receiver is not as great. Most methods of generating antenna-current pulses lend themselves readily to controlling the magnitude of the current and, hence, the radiated signal energy.

A final aspect of optimum signal design pertains to controlling the shape of the energy-density spectrum of the signal by controlling the rise and fall times of the antenna current pulse precisely. It is desirable to produce a spectrum having a more nearly constant energy-density over its useful bandwidth. This requires a particular shape that can be determined analytically for the leading and trailing edges of the pulse. Whether this type of control over the pulse shape is feasible is not yet known.

The possibility of altering the pulse shape from pulse to pulse suggests some interesting applications. For example, a mode of operation analogous to frequency hopping can be achieved by changing the pulse rise and fall times from pulse to pulse. This permits the frequencies at which maximum energy density occurs to be changed during operation and enhances the possibility of detecting targets that may have large responses at specific frequencies.

3.4.2 Jamming and Countermeasures

It is relatively easy to jam conventional narrow-band radars because the jamming signal energy can also be concentrated in a narrow band. Typical approaches to jamming conventional radars include tone jamming, swept-frequency jamming, barrage (or noise) jamming, and pulse jamming. In addition to such brute-force techniques there are also "spoofing" techniques, such as repeat jammers, which cause the radar signal to provide incorrect information.

Jamming an impulse radar is likely to be much more difficult. This is because a typical narrow-band jammer signal can be almost totally filtered out at the input to the radar with very little degradation to the desired radar signal. Although there are various ways to achieve this result, use of a channelized input to the radar receiver is convenient for eliminating the jamming signal and provides a means of approximating the matched-filter receiver by controlling the gains of the individual channels. Any channel in which a jamming signal occurs can possibly be switched off while the clear channels remain intact.

The use of a repeat jammer for impulse radar also appears to be fairly difficult. The repeater must have a bandwidth comparable to that of the impulse radar and be able to provide a constant delay throughout this bandwidth. Although this is not impossible to achieve, it is much more difficult than the present approach.

Although impulse radar appears to be fairly immune to conventional jamming techniques, much more analysis is required to evaluate jamming vulnerability completely.

3.4.3 Clutter Rejection Analysis

Clutter is any radar return from objects other than the desired target. For a land-based radar, clutter arises most often when the desired targets are only few degrees above the horizon and results from trees, buildings, hills, ocean waves, etc. For airborne radar looking for targets on the ground, clutter from the ground fills the

entire radar beam and usually represents a signal power considerably larger than the power from the desired target. Conventional radar systems use several different techniques to reduce the effects of clutter. In the case of moving targets, there are ways to cancel returns from stationary objects on a pulse-to-pulse basis. Improving the range resolution also reduces the clutter power in each range cell and enhances the possibility of seeing the target.

The excellent range resolution of impulse radar should minimize the clutter return in each range cell. Not only can this conclusion be obtained from theoretical considerations, but it has also been demonstrated in actual radar tests. An example known to one of the authors (GRC) of this report occurred with the Random-Signal Radar developed at Purdue University in the early 1970's. Although this radar is a spread-spectrum radar rather than an impulse radar, it has a range resolution of about 15 cm and, unlike conventional spread-spectrum radars, has no range sidelobes because successive pulses are statistically independent. Thus, in this regard at least, it is very similar to impulse radar. Tests were performed with this radar by the Navy at Panama City, Florida, in competition with more conventional radars. The targets were hollow steel balls, about 30 cm in diameter, floating in the Gulf at a range of about 1200 m. The Random-Signal Radar was able to detect these floating objects because the 15-cm range resolution reduced the sea clutter by a sufficient amount. No conventional radar was successful in detecting the floating balls because of excessive sea clutter. Thus, it is clear that improving the range resolution does in fact substantially reduce the clutter signal, and impulse radar should be better in this regard than conventional spread-spectrum radar because impulses have no range sidelobes.

The use of improved range resolution to reduce clutter is not an unmixed blessing, however. When the target of interest is substantially larger than the size of the range cell, as it must be for target identification, the energy of the return from each scattering region on the target is substantially less than the total energy re-

turned from the target. Hence, even with reduced clutter there may not be a net improvement in detectability. In general, it is difficult to predict the results without a substantial amount of analysis and a precise knowledge of the target scattering regions and aspect angle.

An important aspect of clutter analysis for impulse radar is to have good models for the return signals from typical clutter sources when they are illuminated by short-pulse EM waves. On the basis of available information, it appears that such clutter signals may be significantly different from typical clutter signals for conventional radar. In a conventional radar, for example, the clutter return looks much like noise and is frequently modeled as additional Gaussian noise in the system. Performance calculations are then made on the basis of the usual Gaussian noise models. For impulse radar, the clutter returns may well look like impulsive noise and have completely different statistics. Whether these different statistics are favorable or unfavorable to the detection process is not yet known.

Another aspect of the clutter performance of impulse radar is its performance in the presence of radar chaff. Typical chaff packages contain dipoles of different sizes so that there are many frequencies at which near-resonant returns occur. The RCS of such chaff for sinusoidal waves may be on the order of 40 m^2 over a frequency range from 3 GHz to 12 GHz [Barton 1988]. However, the return signal will look quite different to an impulse radar. A typical chaff dispersion will result in about one dipole per 17 m^3, which suggests that the average spacing may be on the order of 2.5 m. Because this separation is greater than the range resolution of impulse radar, each chaff dipole produces a distinct return. This should simplify the problem of distinguishing chaff from targets, particularly since the chaff return may fluctuate more from pulse to pulse than the target return. In order to analyze this problem in more detail, it is necessary to determine the time response of chaff dipoles of different sizes to impulse interrogation.

3.4.4 Probability of Intercept and Exploitation

Impulse radar might be applied to situations in which interception of the radar signal is to be avoided. The usual way to give a radar a low probability of intercept is to employ a spread-spectrum signal with a large time-bandwidth product. If the processing gain achievable from the large time-bandwidth product is greater than the range advantage of the intercept receiver, then detection can be avoided. If the processing gain is not large enough (and usually it is not), then LPI performance is achieved by avoidance, that is, by not transmitting at the time and place being examined by the intercept receiver, if possible.

In the case of impulse radar, the time-bandwidth product of the signal is essentially unity. Hence, there is no possibility of using processing gain to avoid detection. On the other hand, the bandwidth is so large that typical intercept receivers can observe only a small fraction of the total transmitted energy. This concept is explored quantitatively below.

Assume that the intercept receiver is using a compressive receiver that is capable of scanning over a 50-MHz bandwidth in 100 μs and that it has a frequency resolution of 5 kHz. These numbers are somewhat representative of existing intercept receiver capabilities and are adequate to detect conventional radar signals. Next, assume that the effective bandwidth of impulse radar signal is 20 GHz. This implies that the fraction of the total signal energy that falls within any one resolution cell of the compressive receiver is 2.5×10^{-7} or -66 dB. Because the range advantage enjoyed by the intercept receiver is likely to be on the order of 50 to 60 dB, there is a 6- to 16-dB margin of protection for impulse radar. This is quite likely to result in a fairly small probability of interception.

The second aspect that is favorable to impulse radar is its very small duty factor. Most intercept receivers search a given solid angle in space in a specified frame time so that time spent in each angular resolution cell may be on the order of 1 ms. If impulse radar is not transmitting during the particular 1 ms that its

angular resolution cell is being interrogated, it will not be intercepted. Hence, the probability of intercept is simply the probability that the very narrow impulse radar pulse falls within a given 1-ms time slot occurring once every frame time. This is also likely to be a small probability, particularly if impulse-radar PRF is low.

Exploitation of a radar signal is the ability to use an enemy radar signal for some purpose, missile homing on the radar transmitter, for example. Obviously, exploitation requires the interception of the radar signal to have already taken place. Homing receivers tend to have a bandwidth that is as wide as the conventional radar bands so that any radar operating within a conventional band will be detected. Because of the extremely large bandwidth of an impulse-radar signal, the fraction of the total signal energy within the pass band of the homing receiver will be small, particularly if impulse radar has its region of maximum energy density outside of the conventional radar bands. Thus, there is a reasonable probability that the homing receiver will not receive sufficient signal energy to accomplish its mission.

3.4.5 Electromagnetic Compatibility

Because any radar must operate in an environment in which communication equipment and other radars are also operating, the potential for interference between systems is great. Unless they are operating in close proximity, conventional narrowband systems are unlikely to be a serious source of interference for impulse radar. However, if these narrowband systems are operating in close proximity to impulse radar and within its antenna beamwidth, the total interference energy delivered into the impulse-radar receiver may be sufficient to seriously degrade performance.

It is unlikely that impulse radar will be a serious source of interference for such narrow-band radar and communication systems, unless they are operated in close proximity. The large peak pulse powers of impulse radar can easily saturate the front ends of most conventional receivers and disable their operation for a period of time that is many times larger than the duration of impulse-radar signal. Modern

communication systems tend to be digital and to utilize extensive error-correction capability. The short pulses from impulse radar, even if they saturate the communication receiver front ends, are not likely to destroy more data than can be corrected by forward burst-error correction.

Nevertheless, there may well be other types of equipment for which the possibility of interference is serious. For example, interference in the sidelobes of angle-tracking systems can cause large errors. Thus, radar fire-control systems, missile-guidance systems, and track-while-scan systems are all potential victims of impulse radar. Because such systems usually operate at frequencies higher than 8 GHz, these difficulties may be alleviated by appropriate spectrum control of impulse radar.

The problem of EM compatibility of impulse radar and conventional systems is indeed a serious one and deserves a great deal of analysis. There are undoubtedly techniques that can ameliorate the situation. For example, peak signal limiting at the inputs to conventional receivers may reduce the amount of interference. Infrequent operation of impulse radar, coordinated with other systems, will also minimize interference. In addition, there are some applications of impulse radar for which the interference may be negligible or non-existent. For example, the ground-penetration application may result in minimal interference if the sensor is close to the ground.

3.4.6 False Alarms, Detectability, and Missed Targets

The probabilities of detection and false alarm are important parameters for any radar system. The analytical determination of these probabilities depends primarily on the assumed fluctuation model of the target, the signal energy per pulse, the type of detection employed, and the receiver noise model.

In conventional radar, target fluctuation results from sinusoidal wave returns from various parts of the target adding vectorially in different ways as the aspect angle changes slightly. This phenomenon is not likely to occur for impulse radar

because the range differences between reflecting points of most targets is likely to be greater than the range resolution. Hence, each reflecting region will appear as a distinct target. This result is fine when target identification is the issue, but it is a serious disadvantage with respect to target detectability because the energy returned from each reflecting region is smaller than the total energy returned from the target. Therefore, the question arises: is there any way of combining all of the energy from a given target before the detection process?

One way of acquiring all of the energy associated with a given target is to employ an energy detector such as the one in Figure 3.4. It can be shown [Torrieri 1981] that the probability of false alarm for such a detector is given by

$$P_{FA} = Q\left[\frac{V_T - 2TB}{2\sqrt{TB}}\right] \tag{3.1}$$

where Q is the ordinary Q-function for the normal probability density function, V_T is the detection threshold, N_0 is the one-sided noise spectral density, and the product TB is greater than about 30. The value of T must be selected large enough so that the integration is over all the returns from the target. It is on this basis that it is reasonable to assume that TB is sufficiently large. However, this large integration time destroys the range resolution of the radar. The corresponding probability of detection for this situation is given by

$$P_D = Q\left[\frac{Q^{-1}(P_{FA}) - (2E/N_0)/2\sqrt{TB}}{\sqrt{1 + (2E/N_0)/TB}}\right] \tag{3.2}$$

where E is the signal energy available in all of the pulses included in the integration time T.

The alternative to energy detection is the use of a matched filter. Unless the target structure is known *a priori*, the matched filter must be matched to a single returned pulse. Although the matched filter provides the maximum signal-to-noise ratio for each return pulse, the energy per pulse will be less than the total energy from the target. Hence, this approach may not provide the greatest detectability.

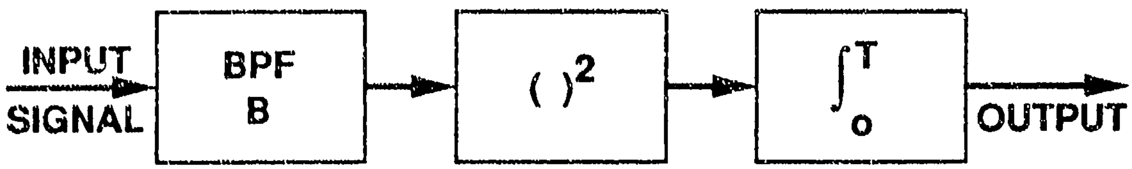

Figure 3.4: The energy detector for impulse radar

If the matched filter is used, however, the probability of false alarm is given by [DiFranco 1968]

$$P_{FA} = Q(V_T) \tag{3.3}$$

and the probability of detection for a single observation of a nonfluctuating target is given by the following equation.

$$P_D = Q\left(V_T - \sqrt{2E/N_0}\right) \tag{3.4}$$

When the issue is target identification rather than detectability, the matched filter is the obvious choice because it provides the greatest range resolution and range accuracy.

As a means of comparing the probabilities of detection for these two type of detectors, assume that we have a target with 10 reflecting regions spanning a range of 100 range cells and that each reflecting region is returning a signal energy so that $2E/N_0 = 20$. If the probability of false alarm is fixed at 10^{-6}, the probability of detection for the energy detector becomes 0.999 while that for the matched filter is only 0.39. This is a clear example of how the choice of detector depends on the application.

3.4.7 Overall Performance Analysis and Comparison

Although no extensive comparisons of overall performance have yet been made between impulse radar and conventional systems, such studies are of great importance and urgency. The analysis presented in Appendix B does make some comparisons of antenna beamwidth and range resolution and finds that these aspects are in reasonable agreement with the conventional wisdom. There are many other aspects of radar performance that also need to be compared. These include the maximum range capability, performance against stealth targets, LPI capability, clutter-rejection capability, and jam resistance.

In addition to comparing impulse radar with conventional radar, it is also essential to compare various system designs for impulse radar itself. Of particular concern here are various methods of generating the antenna-current pulses and various methods for implementing the detection process. For both of these items there is little previous experience to serve as a guide.

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Chapter 4

Critical Issues in Impulse Radar

This chapter deals with a few of the critical issues that must be addressed in any serious investigation of the potential for impulse radar. These issues have been discussed in some detail in previous sections; the intent here is simply to outline aspects that require further consideration and to suggest reasonable approaches. The ordering of these critical issues is not in order of priority, but rather in order of occurrence in the radar process.

4.1 Optimum Signal Design

Each potential application of impulse radar will likely require special consideration as to the signal waveform that is optimum for that particular application. For example, applications that require target detection at large ranges must emphasize techniques that produce the greatest amount of radiated signal energy in each pulse. For these cases, the precise form of the signal is of less importance because the achievement of extremely good range resolution is not necessary. Therefore, relatively slow rise and fall times on the antenna current pulses, but very large maximum currents, are desirable in order to put more energy at the lower frequencies.

On the other hand, if the application involves target identification, then very good range resolution is necessary and target detection is of lesser importance. In this case, obtaining the largest bandwidth of the radiated signal is of great importance and effort must be directed toward achieving very fast rise and fall times and very short duration of the antenna-current pulses. Because the EM scattering process at the target is complex, other considerations, such as polarization effects, must be considered in designing the pulse structure. Therefore, in order to determine the optimum signal design for a particular application, complete and accurate modeling of the various processes will be required.

In either of the above situations, it seems likely that a radiated energy spectrum that is as nearly uniform as possible over the range of useful frequencies is desirable. Achieving such a uniform spectrum requires additional analysis to determine appropriate shapes for the antenna-current pulses. This must be done, of course, with due regard to achieving such shapes with practical hardware.

A second aspect of optimum signal design is that of achieving the greatest possible efficiency in terms of the ratio of the radiated energy per pulse to the stored energy per pulse in the current-pulse generator. As noted previously, the duration of the pulse is almost irrelevant with regard to the radiated energy because the radiated energy depends on the rise and fall times of the pulse. However, both the stored energy in the pulse generator and the shape of the resulting radiated energy spectrum (particularly the peaks and valleys of the spectrum) do depend on the pulse duration. Thus, the relationships among all of these aspects of the pulse shape of the antenna current need to be analyzed in detail.

A third important issue has to do with the possibility and desirability of radiating pulse groups with coded pulse spacings and/or coded amplitudes to increase the energy available without seriously degrading the range resolution. Several analytical techniques for designing such pulse groups are known, but the extent to which they can be implemented with existing hardware is unknown.

A final issue is that of changing the pulse shape from pulse to pulse to achieve both excellent detectability and excellent range resolution concurrently. A subissue is that of power control on individual pulses to enhance the LPI properties of the radiated signal.

4.2 High-Power "Impulse" Generators

Emphasis on impulse-radar R&D for the immediate future will be on applications requiring higher peak power than that used in short-range applications already developed such as ground penetration and intrusion detection. An ideal device for the generation of ultra-short pulses of extremely high peak power is the PCPS described in Section 3.2.1. The parameters of the PCPS can be scaled [Nunnally and Hammond 1983] over many orders of magnitude to satisfy a wide variety of applications.

Redesign for production of PCPS devices is required. For example, the feasibility of integrating the laser and the semiconductor switch into a single device must be considered. Such a redesign for production by a commercial firm is already in progress.

Further modeling and experimentation is required to determine what modification of the PCPS may be desired to facilitate the use of rise-time control in the impulse-radar transmitter. Much of this design can be accomplished using existing PCPS modeling codes [Iverson 1988]. Also, versions of the PCPS device scaled down in peak power ought to be considered for use in existing short-range applications of impulse radar.

4.3 Antenna Design

Design of antennas from transmission and reception of *transient* signals is one of the most critical areas of impulse-radar R&D. As noted earlier, the starting point must

be at the level of basic principles. The standard antenna theory based on sinusoidal excitation will be of little use in impulse-radar R&D.

Analytical studies of proposed antenna designs are difficult to the point of impracticality, even for the simplest configurations. Extensive use of numerical techniques will be required. Existing computer codes, such as TWTD will be used and extended as required. Other time-domain EM codes will need to be developed for use in new types of antennas.

Traveling-wave antennas appear to be one class of antennas applicable to impulse radar. Examples include the classical Beverage and rhombic antennas. More pertinent examples are the impulse-radar antenna developed at RADC [Figure D.2], and the TEM horn used at the University of Texas, Arlington. The dimensions of a traveling-wave antenna are likely to be much greater than the distance light travels in the rise time of the antenna current; 10–100 ps $\Rightarrow$ 3–30 mm. Thus, dispersion effects in antennas must be carefully considered in the design of impulse-radar systems.

Materials science studies of radome materials for transmission of UWB signals are also critically needed in impulse-radar R&D. Dispersion and refraction effects of radomes on impulse-radar signals must be studied and taken into account in system design.

4.4 Transient Electromagnetic Theory

One of the principal reasons for pursuing the development of impulse radar is that certain highly desirable, "advanced" radar capabilities may be achievable. These capabilities include, but are not limited to, target identification, target imaging, "stealth" target detection, and various "penetration" capabilities. Regardless of whether advanced or rudimentary capabilities are being considered, the fundamental processes governing impulse-radar operation and performance are *transient* elec-

tromagnetic processes. In particular, *all* applications of impulse radar require the emission, propagation, scattering, and reception of short-duration, electromagnetic pulses. This sequence of transient electromagnetic processes is the foundation on which impulse radar is based. The development of impulse radar will, therefore, require a strong effort in the formulation and solution of transient electromagnetic problems.

In recent years, there has been a substantial expansion of interest in the engineering application of linear electromagnetic wave theory, especially in areas involving penetration and scattering interactions with electrically large complex structures. This interest is driven primarily by the need to understand the characteristics of the RCS of complex targets for conventional sinusoidal radar signals. Typical structures of engineering interest have shapes, apertures, cavities, and material compositions which produce near fields that cannot be resolved into finite sets of modes or rays. Generally, electromagnetic wave interactions with such structures pose intractable problems when addressed by existing analytical and asymptotic theories. Therefore, computational approaches *must* be used to address these important problems.

Accurate numerical computation of full-vector electromagnetic wave interactions with arbitrary structures is difficult but necessary for the development of impulse radar. These computations are required not only for the analysis of RCS and the scattering of transient electromagnetic wave, but also for the development of antenna structures for the transmission and reception of impulse radar signals. For effective formulation and solution, the transient electromagnetic processes in impulse radar require a time-domain approach rather than the frequency-domain approach traditionally used in engineering electromagnetics.

Appendix A provides an overview of time-domain EM theory and presents a quintessential problem in transient EM scattering and transient excitation of antennas.

4.5 Receiver Design

The design of a receiver for impulse radar signals is critically dependent on the intended application for the radar. As noted in a previous section, the range resolution of impulse radar is likely to be sufficiently good so that individual returns from separate scattering regions on a target of reasonable size are distinct. Since each distinct return has less energy than the sum of the energies from all of the scattering points, the target detectability suffers unless some method of combining signal energies can be achieved. One approach to doing this, the energy detector, is outlined in Section 3.4.6 in a discussion of the probabilities of false alarm and detection. By making the integration time of the energy detector long enough to include all of the returns from the target, one can substantially increase the probability of detection. The penalty for this improvement is that the effective range resolution is now degraded to a value that is approximately the same as the size of the target.

However, the energy detector does not use the available signal energy in the most effective manner. To achieve the largest output signal-to-noise ratio, it is necessary to employ a matched filter that is matched to the returned signal. This implies that for a complex target, the matched filter must be matched to the sum of all returns from all scattering regions on the target. If this were actually possible, the probability of detection would be much greater than that possible with the energy detector. Unfortunately, the only way to do this is to know the precise nature of the target *before* it is detected — a very unlikely circumstance. However, even in this idealized situation, the individual scattering regions are not resolved so the range resolution is again degraded.

To retain the range resolution it is necessary that the receiver matched filter is matched to the return signal from each individual scattering region on the target. Since the return from each individual scattering point is likely to be a replica of the transmitted signal, the construction of such a matched filter is possible, at least

in theory. In practice, it is necessary to approximate impulse response of the ideal matched filter. This point is discussed in more detail below.

An alternative to the matched filter is to cross-correlate the received signal with an appropriately delayed replica of the radiated signal (*not* a replica of the antenna-current pulse). This method is exact and does not involve any approximations. The problem with this approach is that a different replica of the radiated signal and a separate correlator are needed for each range cell. Although such an approach is possible in theory and has some very attractive features, it is very hardware intensive.

The above discussion reveals two conflicting requirements on the design of an impulse radar receiver, depending on whether the primary goal is target detection or range resolution. Fortunately, there appears to be a way of approximating both objectives within the same receiver. This approach requires parallel channels in the receiver input, each covering a portion of the total signal bandwidth and each with individually controlled gains. The detectability of the energy detector is achieved by setting all gains equal and summing the outputs of the channels into a square-law device and integrator. The matched filter can be approximated by adjusting the gain of each channel to be proportional to the average amplitude of the radiated signal frequency spectrum within the channel spectrum. Thus, it is possible to visualize a dual-mode method of operation in which the approximate energy detector is used for initial target detection, and the approximate matched filter is used for target identification. A critical issue in the design of such a parallel-channel receiver is that of achieving sufficient phase linearity in each channel to avoid seriously distorting the signal.

Another critical issue in receiver design is that of providing sufficient isolation between the transmitter and the receiver. The usual isolation devices, such as balanced duplexers and ferrite circulators, are inherently narrow-band devices and are unlikely to be useful in impulse radar. Probably the most effective approach is to

use separate antennas for transmission and reception and use spatial isolation. Even in this case, however, it may be necessary to employ shorting switches at the receiver input to reduce direct signal feed-through sufficiently. The main disadvantage is an increase in the minimum range of the radar because of nonzero switching times.

4.6 Signal Processing and Analysis

Processing and analysis of the received signal is another critical issue. Signal processing and analysis is of particular importance when advanced radar capabilities such as target identification and target imaging are considered. The major aspects of this issue were outlined in some detail in Section 3.2.4, and are summarized here.

The principal objectives of signal processing and analysis are to extract the signal containing information about the target from the output signal of the receiver and then to extract information about the target from that signal. Of particular importance is the determination of optimum transmitted signal structures for a particular application through the complete modeling of the impulse-radar process. It is essential that approaches to signal processing and analysis be developed prior to the final design of the impulse-radar system.

A detailed study of various signal-processing methods should be undertaken. This study should evaluate the performance of energy detectors, matched filters, and cross-correlators for the receiver and, for the major applications of the impulse radar, make recommendations as to the type of signal processing that is most suitable. Of particular concern is the feasibility of hybrid-processing methods that might be required for target detection and target identification.

A final critical signal-processing issue is that of performing the necessary processing tasks when several targets are present. This is of particular concern in track-while-scan systems and in target-discrimination systems.

Appendix A

Time-Domain Electromagnetics

The complex physical processes involved in impulse radar reside primarily in the domain of classical electromagnetics. The equations of classical electromagnetics, Maxwell's equations, are *partial* differential equations (PDEs) for the electric and magnetic fields as a function of spatial position and *time*. However, the exposition of EM theory often presents Maxwell's equations in the frequency domain. This is accomplished through the application of the Fourier transform and results in *ordinary* differential equations (ODEs) for the electric and magnetic fields as a function of spatial position. Under the Fourier transform, time, which is an independent variable in Maxwell's equations, becomes frequency, which is a parameter in the resulting ODEs and not an independent variable. Frequency then becomes an important parameter in the subsequent theoretical development and in the solution of practical problems in physics and engineering. This approach has proven useful in classical communications and radar systems engineering which involves signals characterized by narrow relative bandwidths.

Impulse radar involves EM excitations that are transient signals having a wide relative bandwidth. Therefore, it is more natural and efficient to formulate the mathematical equations governing the physical processes in terms of Maxwell's equations in the time domain. Although frequency-domain ideas are still useful, the problems to be addressed in impulse radar are better approached using Maxwell's

equations in their original form in terms of spatial position and *time*. Also, many of the measurements required in impulse-radar research and development are best made in the time domain. Study of literature on impulse radar and related theory and technology shows that most of the recent progress has been based on analyses and measurements in the time domain. This Appendix presents an overview of theory and problems in the important area of *time*-domain electromagnetics.

A.1 Maxwell's Equations

This section provides a basic introduction to *time-dependent* or *transient* EM theory, beginning with Maxwell's equations, as it applies to problems of importance to UWB radar. Maxwell's equations describe the evolution of EM field quantities and can be written in MKS rationalized units as:

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \tag{A.1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{A.2}$$

$$\nabla \cdot \mathbf{D} = \rho \tag{A.3}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{A.4}$$

where $\mathbf{E}$ and $\mathbf{D}$ are the electric field and displacement vectors, $\mathbf{H}$ and $\mathbf{B}$ are the magnetic field and induction vectors, $\mathbf{J}$ is the conduction current density, and ρ is the electric charge density. Equation (A.1) is Amperes's law to which Maxwell added the displacement-current term $\frac{\partial \mathbf{D}}{\partial t}$ which is required to make the system of equations consistent. Equation (A.2) is Faraday's law, equation (A.3) is Coulomb's law, and equation (A.4) states the absence of magnetic monopoles. Equations (A.3) and (A.4) represent auxiliary conditions on the principal Maxwell equations (A.1) and (A.2).

For macroscopic media, the dynamical response of the aggregate atoms is summarized in the constitutive relations.

$$\begin{aligned} \mathbf{D} &= \epsilon \mathbf{E} && \text{(A.5)} \\ \mathbf{J} &= \sigma \mathbf{E} && \text{(A.6)} \\ \mathbf{B} &= \mu \mathbf{H} && \text{(A.7)} \end{aligned}$$

In general, the electric permittivity ϵ, the electric conductivity σ, and the magnetic permeability μ are tensors. However, for the purposes of this report on UWB radar, the media of interest will initially be considered as being isotropic, so ϵ, σ and μ reduce to scalar parameters.

Maxwell's equations consist of a set of four coupled first-order PDEs relating the various components of electric and magnetic fields. It is useful to introduce two potentials, which allow these four first-order equations to be written as two second-order equations. These potentials are the scalar electric potential ψ and the magnetic vector potential $\mathbf{A}$. Since $\nabla \cdot \mathbf{B} = 0$, $\mathbf{B}$ can be defined in terms of a vector potential $\mathbf{A}$.

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{A.8}$$

Faraday's law (A.2) can then be written as

$$\nabla \times \left[\mathbf{E} + \frac{\partial \mathbf{A}}{\partial t}\right] = 0 \tag{A.9}$$

This means that the quantity with the vanishing curl in equation (A.9) can be written as the gradient of a scalar function, namely, the scalar electric potential ψ.

$$\mathbf{E} + \frac{\partial \mathbf{A}}{\partial t} = -\nabla \psi \tag{A.10}$$

$$\mathbf{E} = -\nabla \psi - \frac{\partial \mathbf{A}}{\partial t} \tag{A.11}$$

The definition of $\mathbf{B}$ and $\mathbf{E}$ in terms of the potentials $\mathbf{A}$ and ψ according to equations (A.8) and (A.11) satisfies identically the two homogeneous Maxwell equations. The two inhomogeneous equations determine the dynamic behavior of $\mathbf{A}$ and ψ. We can write these two inhomogeneous equations in terms of $\mathbf{A}$ and ψ .

$$\nabla^2 \mathbf{A} - \epsilon\mu \frac{\partial^2 \mathbf{A}}{\partial t^2} - \nabla \left[\nabla \cdot \mathbf{A} + \epsilon\mu \frac{\partial \psi}{\partial t} \right] = -\mu \mathbf{J} \tag{A.12}$$

$$\nabla^2 \psi + \frac{\partial}{\partial t} \nabla \cdot \mathbf{A} = -\frac{1}{\epsilon}\rho \tag{A.13}$$

The set of four Maxwell equations has been reduced to a set of two coupled equations, (A.12) and (A.13), by introducing the potentials $\mathbf{A}$ and ψ. These equations can be uncoupled by exploiting the fact that an arbitrary factor can be added to the definition of the potentials. For the definition of $\mathbf{B}$ in terms of $\mathbf{A}$, the choice of $\mathbf{A}$ is arbitrary in that the gradient of some scalar function ς can be added. Thus the definition of $\mathbf{B}$ is left unchanged by the following transformation.

$$\mathbf{A} \longrightarrow \mathbf{A} + \nabla\varsigma \tag{A.14}$$

In order that the definition of the electric field $\mathbf{E}$ remain unchanged, the simultaneous transformation

$$\psi \longrightarrow \psi - \frac{\partial \varsigma}{\partial t} \tag{A.15}$$

is required. The potentials $\mathbf{A}$ and ψ are now free to be chosen such that

$$\nabla \cdot \mathbf{A} + \epsilon\mu \frac{\partial \psi}{\partial t} = 0 \tag{A.16}$$

which is referred to as the Lorentz gauge. This particular gauge uncouples equations (A.12) and (A.13) which can then be written as follows.

$$\nabla^2 \mathbf{A} - \epsilon\mu \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu \mathbf{J} \tag{A.17}$$

$$\nabla^2 \psi - \epsilon\mu \frac{\partial^2 \psi}{\partial t^2} = -\frac{1}{\epsilon}\rho \tag{A.18}$$

This set of two uncoupled second-order equations, along with equation (A.16), is equivalent to the four Maxwell equations in every respect. These equations are hyperbolic and exemplify the propagating nature of EM disturbances. The quantity $\epsilon\mu$ is related to the velocity of propagation U of EM radiation by the following equation.

$$U = \frac{1}{\sqrt{\epsilon\mu}} \tag{A.19}$$

The electric permittivity ϵ and the magnetic permeability μ are generally written in terms of their free space values, ϵ_0 and μ_0, times their values relative to free space, ϵ_r and μ_r.

$$\epsilon = \epsilon_r \epsilon_0 \tag{A.20}$$

$$\mu = \mu_r \mu_0 \tag{A.21}$$

The value of the free space permittivity is $\epsilon_0 = 8.845 \times 10^{-14}$ F/cm and the value of the free space permeability is $\mu_0 = 4\pi \times 10^{-9}$ H/cm. The velocity of propagation can then be written as

$$U = \frac{1}{\sqrt{\epsilon_r \mu_r}} \frac{1}{c} \tag{A.22}$$

where $c = 1/\sqrt{\epsilon_0 \mu_0}$ is the velocity of light in free space.

These equations are given without a reduction to "harmonic" form and, therefore, represent the governing equations for complete time-dependent problems of EM theory.

A.2 Transient Electromagnetic Scattering

The application of EM scattering theory to the analysis of the scattering of UWB radar signals by a target can be demonstrated in the context of a classical EM scattering problem. The problem to be considered is that of a transient EM field generated by a current-sheet source and scattering from a dielectric slab having a perfectly conducting backplane. The problem is presented here as a one-dimensional formulation derived by assuming an infinitely extended planar structure. Although this formulation may not appear to represent a physically relevant problem, it does in fact contain the essential features of an entire class of physically important problems and represents a model that would provide a first step towards understanding a number of critical features of UWB radar.

To begin the formulation of this specific problem, consider Maxwell's equations in the time domain, as presented in section A.1, for the case of an excitation having the form of an impulse-radar signal with a temporal structure given by $f(t)$. Spatially, the excitation source is assumed to consist of an infinitely extended, y-directed, current sheet **J** confined to a region of zero thickness at a position $x = d \geq 0$ in the y, z plane. The current-sheet is parallel to and located at a distance d from the near surface ($x = 0$) of a dielectric slab of thickness h that is also infinitely extended in the y-z plane. The far surface of the dielectric slab ($x = -h$) is terminated by a perfect conductor. The current-sheet, having the temporal structure $f(t)$, produces a wideband radiating field that scatters from the dielectric-slab target structure.

The theory of *Green's functions* is utilized in obtaining the full time-dependent solution to this problem, so the form of the driving current to be considered initially is

$$\mathbf{J}(\mathbf{r}, t) = \delta(x - d)\delta(t)\hat{y} \tag{A.23}$$

where $\mathbf{r}$ is the Cartesian spatial-position vector, the function δ is the Dirac delta function, and $\hat{y}$ is the unit vector in the y direction. The complete solution for the case of UWB radar excitation can be found formally by a convolution of the solution obtained for the delta-function excitation (the Green's function) with the wideband-radar temporal function $f(t)$.

Assume also that the material parameters as well as the problem geometry are independent of y and z.

$$\frac{\partial}{\partial y} = \frac{\partial}{\partial z} = 0 \tag{A.24}$$

With this assumption, Maxwell's equations (A.1) and (A.2) reduce to the coupled partial differential equations for the field components E_y and H_z.

$$\frac{\partial E_y}{\partial x} = -\mu \frac{\partial H_z}{\partial t} \tag{A.25}$$

$$-\frac{\partial H_z}{\partial x} = \delta(x - d)\delta(t) + \sigma E_y + \epsilon \frac{\partial E_y}{\partial t} \tag{A.26}$$

All other field components equal to zero. In equations (A.25) and (A.26), the field components E_y and H_z are functions of x and t only. Because it is assumed that σ, μ, and ϵ are constants throughout the region of interest, the equations (A.25) and (A.26) are linear.

The time-domain problem is now transformed to a frequency-domain problem by the application of the Fourier integral. The Fourier integral transformation of a time-domain function $g(x,t)$ into a frequency-domain function $\hat{g}(x,\omega)$ is defined as follows.

$$\mathbf{F}\left[g(x,t)\right] = \int_{-\infty}^{\infty} g(x,t)e^{-i\omega t}dt = \hat{g}(x,\omega) \tag{A.27}$$

Applying the Fourier transform defined in equation (A.27) to equations (A.25) and (A.26), and considering the resulting equations as defining a boundary-value problem in the form of ordinary differential equations in the spatial variable x with the frequency variable ω as a parameter yields

$$\frac{d}{dx}\hat{E}_y(x;\omega) = -i\omega\mu\hat{H}_z(x;\omega) \tag{A.28}$$

$$-\frac{d}{dx}\hat{H}_z(x;\omega) = \delta(x-d) + i\omega\acute{\epsilon}\hat{E}_y(x;\omega) \tag{A.29}$$

where $\acute{\epsilon}$ is the *complex permittivity* defined as follows.

$$\acute{\epsilon} = \epsilon + \frac{\sigma}{i\omega} \tag{A.30}$$

Equations (A.28) and (A.29) can be combined to form a Helmholtz wave equation for the electric field

$$\frac{d^2\hat{E}_y}{dz^2} + \kappa^2\hat{E}_z = i\omega\mu\delta(x-d) \tag{A.31}$$

where κ is the *complex wave number.*

$$\kappa = \omega(\mu\acute{\epsilon})^{1/2} \tag{A.32}$$

The field $\hat{H}_z$ can be found directly from $\hat{E}_y$ using equation (A.6).

The solution of this problem requires the consideration of both regions, the interface at $x = 0$, and the boundary at $x = -h$. In the first region, $0 \leq x \leq d$, the

medium is considered to be free space. Therefore, ϵ and μ take on their free space values ϵ_0 and μ_0, respectively, and $\sigma \equiv 0$. The second region is that of the dielectric slab, $-h \leq x \leq 0$, and is characterized by $\epsilon = \epsilon_s$, $\sigma = \sigma_s$, and $\mu = \mu_s = \mu_0$. In the free-space region, the complex wave number κ_0 is given by

$$\kappa_0 = \omega(\mu_0\epsilon_0)^{1/2} = \frac{\omega}{c} \tag{A.33}$$

and in the dielectric-slab region, the complex wave number κ_s is given by

$$\kappa_s = \omega\left[\mu_0\epsilon_s\left(1 + \frac{\sigma_s}{i\omega\epsilon_s}\right)\right]^{1/2} = \frac{\omega}{c}\left[\epsilon_r\left(1 + \frac{\sigma_s}{i\omega\epsilon_s}\right)\right]^{1/2} \tag{A.34}$$

where ϵ_r is the relative permittivity (dielectric constant) of the dielectric slab.

The solution of this two-region problem requires techniques from the applied mathematics of boundary-value problems where the matching of solutions at the interface $x = 0$ and at the boundary $x = -h$ is required. The formal solution for the electric field $\hat{E}_y$ in the two regions is given as follows. For the free-space region, bounded by the current sheet at $x = d$ and the near surface of the dielectric slab at $x = 0$, the solution is found to be

$$\hat{E}_{yo} = -i\omega\mu_0\frac{\sin\kappa_0 x}{\kappa_0}e^{i\kappa_0 d} + E_I e^{-i\kappa_0 x} \tag{A.35}$$

and for the dielectric-slab region $-h \leq x \leq 0$, the solution is found to be

$$\hat{E}_{ys} = \frac{\sin\kappa_s(x + d)}{\sin\kappa_s d}E_I \tag{A.36}$$

where E_I is the electric field at the interface $x = 0$ given as follows.

$$LE_I = [i\kappa_0 + \kappa_s\cot(\kappa_s h)]\,E_I = -i\omega\mu_0 e^{-i\kappa_0 d} \tag{A.37}$$

The final step in obtaining the complete solution $E_y(x,t)$ to this EM scattering problem is to perform a convolution by multiplying the frequency-domain solution given above for the case of impulse excitation with the Fourier transform $\hat{f}(\omega)$ of the particular temporal impulse function $f(t)$ of interest, and then to transform the result back into the time domain using the inverse Fourier transform.

$$E_y(x,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\hat{f}(\omega)\hat{E}_y(x,\omega)e^{i\omega t}\,d\omega \tag{A.38}$$

When this operation is performed for the free-space region by substitution of equation (A.35) into (A.38), the result is

$$E_y(x,t) = -\frac{\eta_o}{2}\left[f\left(t+\frac{x-d}{c}\right) - f\left(t-\frac{x+d}{c}\right) + \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{\hat{f}(\omega)e^{i\omega(t-(x+d)/c)}}{1-i(k_s/k_o)\cot k_s h}d\omega\right] \tag{A.39}$$

where η_o is the intrinsic impedance of free space. The integral in equation (A.39) can be solved by the calculus of residues. This equation represents a general solution to transient EM scattering problem for arbitrary excitation.

A.3 Transient Excitation of Antennas

Time-domain electromagnetics provides the basis for analysis and design of transmitting and receiving antennas for impulse radar. Computer modeling using numerical solutions of EM problems will be the main tool for these design studies. Low-power short-range measurements based on time-domain reflectometry will be used to verify the performance predicted by the design studies. High-power measurements may be deferred until later stages of the R&D program.

Beamwidths of individual antenna elements are expected to be broad. Substantial antenna gain will, therefore, have to be provided through the use of antenna arrays.

Preliminary studies of impulse-radar antenna arrays [Appendix B] indicate the need to study interaction of off-axis response with the matched filters used in the receiver. This additional complexity may be offset by the ability to obtain additional information in the radar returns, as compared with conventional radar.

TWTD codes may be used for the analysis and design of some classes of antennas. However, some of the new types of antennas required for impulse radar must be modeled using other approaches such as finite-difference or Galerkin finite-element algorithms. Traveling-wave antennas, in particular, will require careful modeling and analysis using these new codes.

As noted in Section 3.2.2, there are substantial differences between the performance of an antenna or an array excited by extremely short transients as compared with that produced by steady-state sinusoidal excitation. One of the most important of these differences is that, in general, the reciprocity theorem for antennas does *not* hold for transient excitation. Robert Kelly has derived conditions for reciprocity in the case of transient excitation and is preparing a paper on this subject.

Standard antenna theory is based on the assumption of sinusoidal excitation. For example, proofs of reciprocity theorems in textbooks on EM theory depend on this assumption. The UWB signal of an impulse radar cannot be approximated by a sinusoid. Removal of the assumption of sinusoidal excitation requires us to reconsider antenna reciprocity starting from basic EM principles.

Consider the widely known theorem that the far-zone pattern of gain vs. angle for a given antenna is the same for reception as for transmission of a sinusoidal waveform. Does this theorem hold for an arbitrary transient signal? Study of this question is complicated by the fact (Appendix B) that the waveform of the far-zone radiation varies with angle. Thus, the pattern of an impulse-radar antenna cannot be described as a scalar function of angle as in the simple case of sinusoidal excitation. However, this complication does *not* imply that transmit-receive reciprocity fails for transient excitation.

Initial study of the problem indicates that transmit-receive reciprocity *does* hold in several examples of array patterns. Further work is needed to determine conditions for transmit-receive reciprocity in general for antenna elements and arrays.

Appendix B

Impulse-Radar Signals

This appendix presents a summary of work that has been done in defining reasonable characteristics for the transmitted signal for an impulse radar and in determining the return signal when an array antenna is used with a matched-filter receiver. The first step is to find solutions for the current in a circuit that might conceivably be used to generate short pulses in the transmitting antenna of an impulse radar. Considered next is the far-zone electric field when an array of such antennas is used. Finally, the return signal from an idealized point target is determined and the response of a matched filter to this return signal is evaluated.

B.1 Preliminary Analysis

A paper by Harmuth [Harmuth 1983b] outlines some conditions on the antenna current that are necessary in a physicallv realizable situation. Specifically, the author points out that the far-zone radiated electric field intensity is proportional to the time-derivative of the antenna current and that there is a time-dependent radiation resistance for the Hertzian dipole.

Harmuth also notes that, because the energy radiated must be equal to the energy delivered to the radiation resistance, there are some constraints on the antenna current. In particular, if the current is required to be zero before zero time, then the

initial value of the current and its time-derivative must also be zero immediately after zero time. These initial conditions can be used in solving for a physically realizable antenna current.

In order to carry out a preliminary analysis, it was convenient to assume the existence of a model to represent a simple circuit that might reasonably be expected to satisfy all of the initial conditions. Furthermore, it was assumed that this circuit was excited by means of a voltage source and a switch that is closed for some short period of time. It is recognized that such a simple model cannot truly represent the actual physical situation, which must necessarily involve distributed parameters.

The antenna current that resulted from the assumed combination of circuit elements can then be determined from circuit theory, taking into account the time variation of radiation resistance.

Since the far-zone electric field is proportional to the time-derivative of the current, this quantity can then be computed. An item of particular interest is the energy spectrum of the radiated EM field, which is obtained from the square of the magnitude of the Fourier transform of the time-derivative of the antenna current. Since the analytical expression for the Fourier transform of the derivative of the current turns out to be quite complicated, and since computed values of the derivative are available, the Fourier transform can be obtained by computing a Fast Fourier Transform (FFT) of samples of the current derivative. The squared magnitude of this transform, normalized to its maximum value, can then be obtained.

B.2 An Alternate Analysis

The preliminary analysis outlined in the previous section is complicated by the need to solve a nonlinear differential equation of second order and third degree. The resulting solution for the antenna current is quite complicated and it is not feasible to do much analytical work with that waveform. Further work is required in nu-

merical computation based on the preliminary analysis to obtain results applicable to studies on impulse radar.

In order to proceed now with an initial study of transmitted and received signals in impulse radar, a more tractable waveform for analysis is required. The basic form of the antenna current, expressed in terms of normalized time $x = t/T$, is selected as follows.

$$i(x) = I_0 T x e^{-\alpha T x} \sin \beta T x, \;\; x \geq 0 \tag{B.1}$$

This current is displayed in Figure B.1 for $\alpha T = 2$ and $\beta T = 2$. The time-derivative of this current, expressed as a function of x, is

$$\frac{di}{dt} = I_0 \left[(1 - \alpha T x) e^{-\alpha T x} \sin \beta T x + \beta T x e^{-\alpha T x} \cos \beta T x \right], \;\; x > 0 \tag{B.2}$$

and this waveform, which is proportional to the far-zone electric field, is displayed in Figure B.2. The corresponding energy-density spectrum for the far-zone electric field is shown in Figure B.3.

It is of interest to look at some numerical values that might represent a practical situation. Suppose, for example, that the 10 to 90 percent rise time of the antenna current pulse is 10 ps. From Figure B.1 it may be noted that this rise time occupies about $0.4T$. Hence, $T = 25$ ps. From Figure B.2 the maximum of the energy spectrum occurs at about $fT = 0.4$, which corresponds to an actual frequency of 16 GHz. The corresponding half-energy points of the spectrum are at about 9.2 GHz and 31.2 GHz, which yields a bandwidth of 22 GHz.

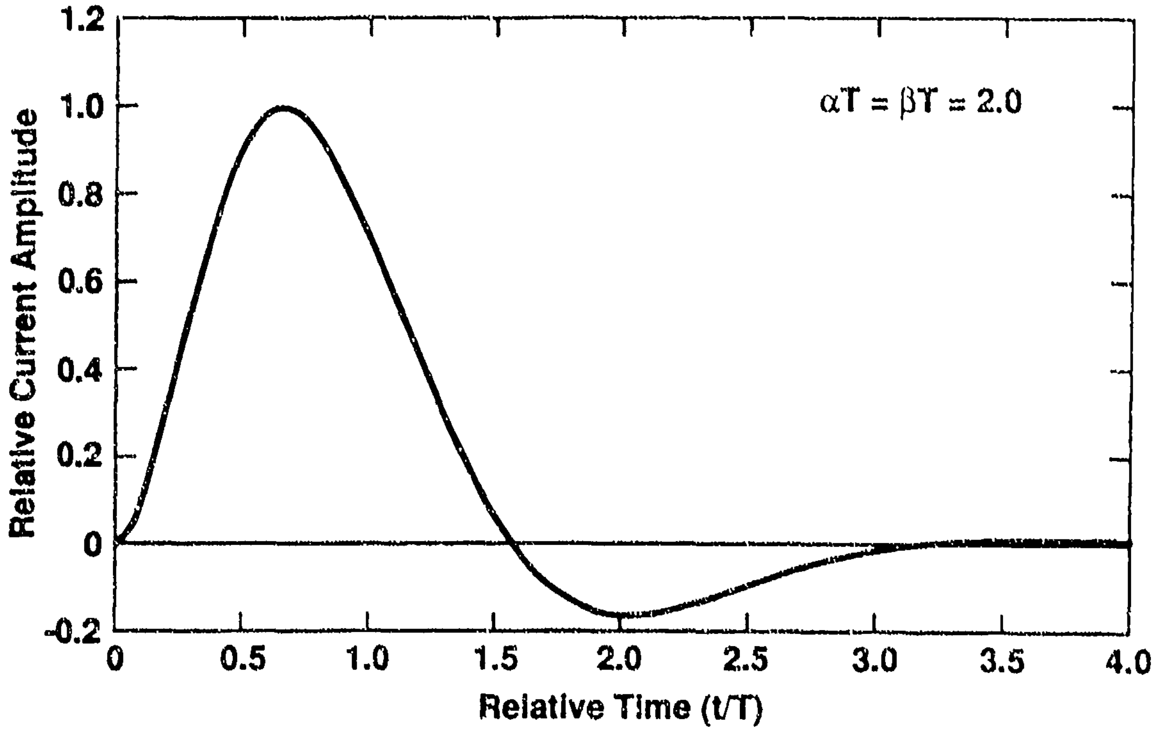

Figure B.1: Typical current pulse in one array element

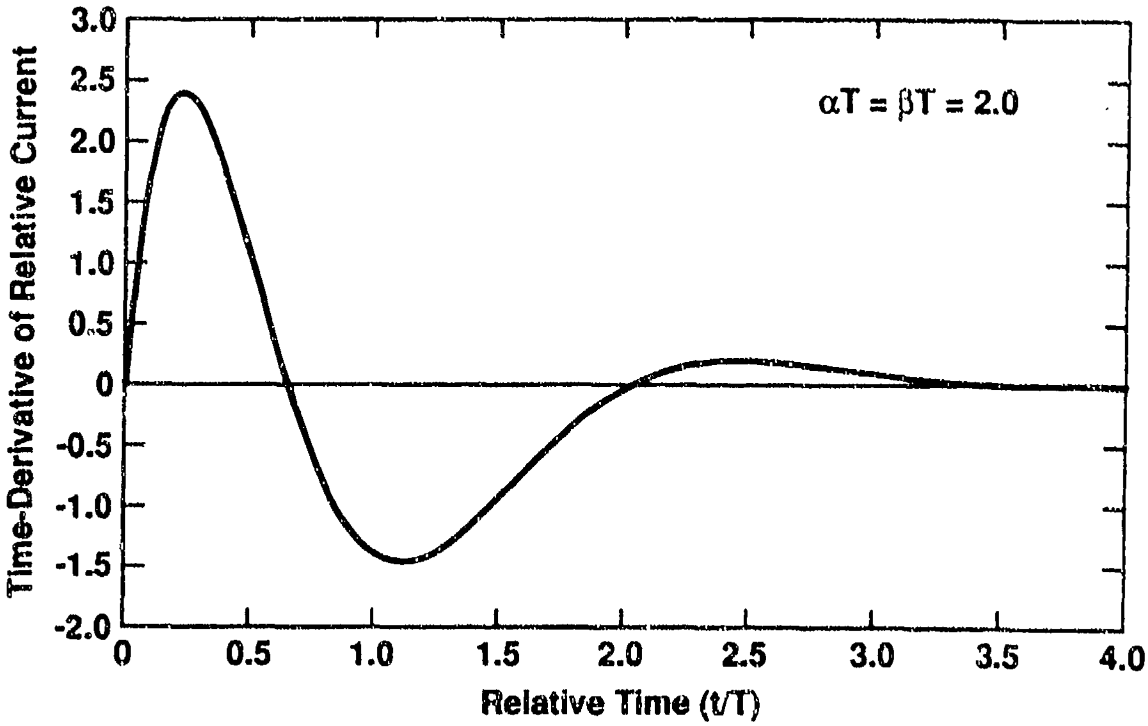

Figure B.2: Time-derivative of current pulse in each array element

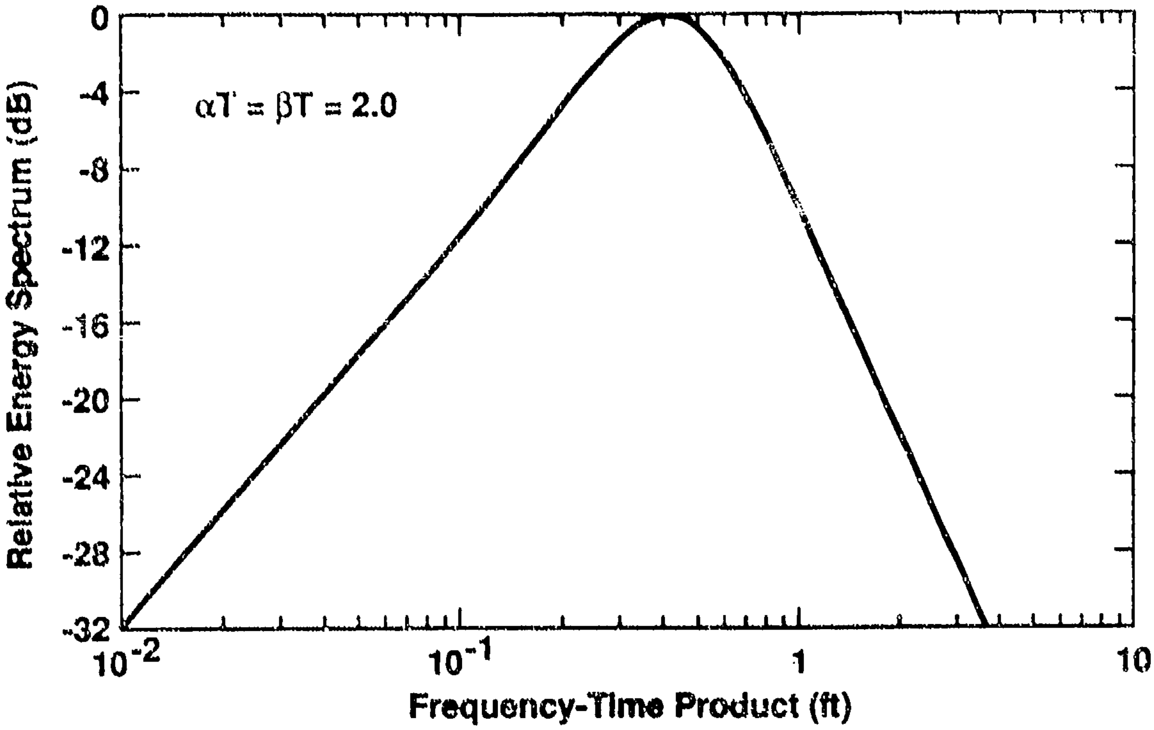

Figure B.3: Energy spectrum of radiated signal from each element of the array

B.3 Array Antennas for Impulse Radar

A single current element does not provide significant directivity in a transmitting antenna for an impulse radar. However, the use of array antennas does provide a method for achieving reasonable directivities, although there are some significant differences in the performance of such arrays with UWB signals. Perhaps the most significant difference is that the waveform of the electric field intensity is a function of the angle away from the antenna axis. This dependence on angle is examined in some detail here because it has considerable impact on the optimum processing of the received signal.

Consider a linear array of current elements spaced d meters apart as shown in Figure B.4. Assume that these are vertical elements so that the angle ϕ is the azimuth angle measured from the normal to the line of the array. The analysis can

easily be extended to include both elevation and azimuth, but this is not done here in the interest of brevity.

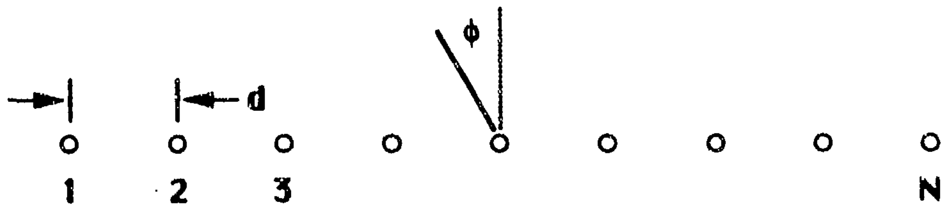

Figure B.4: A linear array of N current elements

When this array is used as a transmitting antenna, the far-zone electric field intensity is simply the sum of the contributions from each current element. The electric field due to the current in the j^{th} element is $E_j(t)$.

$$E_j(t) = \frac{Z_0 s}{4\pi c r} \frac{d i_j(t - r/c)}{dt} \tag{B.3}$$

$Z_0 = 377\,\Omega$

s = length of each array element, in meters

r = distance from the array, in meters

c = 3×10^8 meters/second

The resulting electric field at any angle ϕ is simply

$$E(t, \phi) = \sum_{j=1}^{N} E_j \left[t - (j-1)\frac{d}{c}\sin\phi \right] \tag{B.4}$$

or, in terms of the normalized time x, we have $E(x, \phi)$.

$$E(x, \phi) = \sum_{j=1}^{N} E_j \left[x - (j-1)\frac{d}{cT}\sin\phi \right] \tag{B.5}$$

The directivity pattern of an antenna is usually defined in terms of the ratio of the average power density radiated in a given direction to the maximum value of the average power density. In the case of impulse radar, it is more appropriate to

define directivity in terms of energy density rather than average power density. The energy density in a given direction ϕ is defined as follows.

$$\mathcal{E}(\phi) = \int_0^{\infty} [E(t,\phi)]^2 \, dt \tag{B.6}$$

This function has been evaluated numerically at each value of ϕ and divided by the value of $\mathcal{E}(0)$. The half-energy beamwidth is the difference in ϕ-values at which the energy density drops to one-half of its value at $\phi = 0$.

The directivity of the array depends upon both the spacing of the antenna elements and the length of the pulse. The directivity of a ten-element array for the particular case of $d/cT = 1.0$ is illustrated in Figure B.5. The same current pulse is assumed in each array element. It may be noted that the half-energy beamwidth is about 10°.

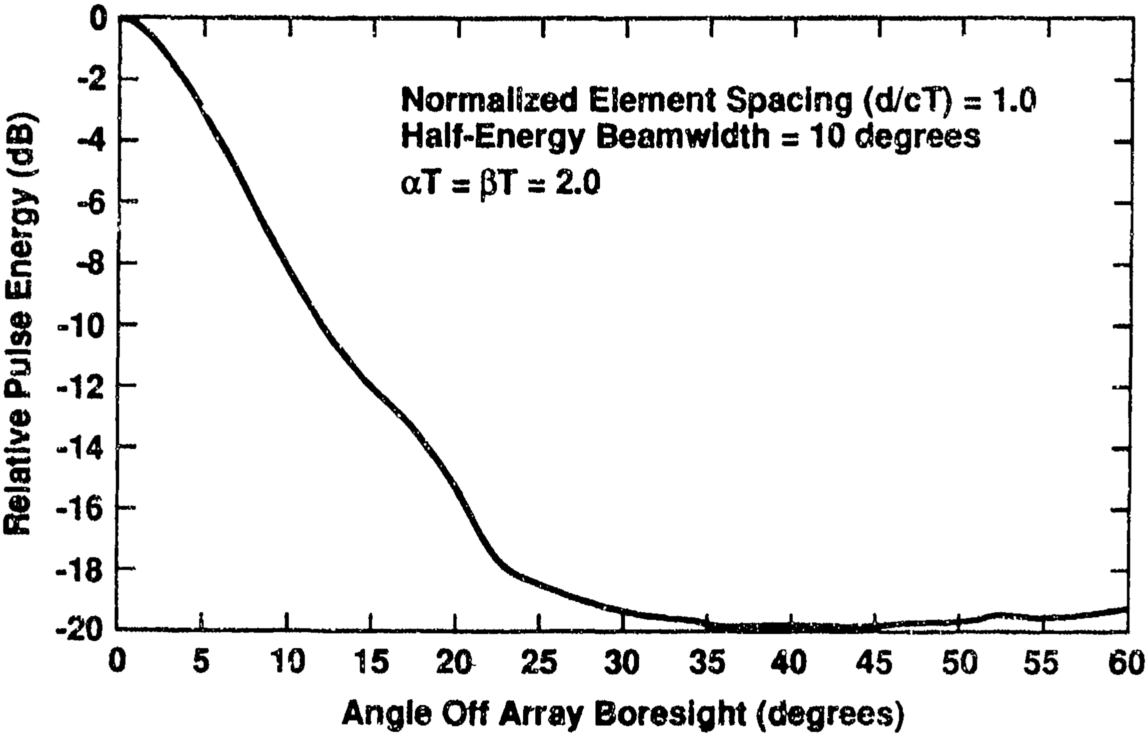

Figure B.5: Directivity of ten-element array

A significant characteristic of the energy patterns displayed in these figures is the absence of any sidelobe structure. A linear array with uniform excitation would have a pronounced sidelobe structure with the largest sidelobe being down by about 13 dB. Although this array also has uniform excitation, these sidelobes are entirely missing.

It is of interest to compare the short-pulse directivity of the array with the directivity that would be achieved with sinusoidal waves. For the previously discussed value of $T = 25$ ps, a value of $d/cT = 1$ leads to a value of $d = 0.0075$ m. A ten-element array therefore has a total length of $9 \times .0075 = .0675$ m. At a frequency of 16 GHz (i.e., the frequency at which energy spectrum is a maximum) the half-power beamwidth for a uniform linear array is approximately 15°.

$$\Theta = \frac{\lambda}{(N-1)d} = \frac{.01875}{.0675} = 0.2778\,\text{rad} = 15.9° \qquad \text{(B.7)}$$

Since the half-energy beamwidth is 10° for this case, it seems that the array has somewhat greater directivity in the short-pulse case. However, if the comparison is made at the upper half-energy point of the spectrum (31.2 GHz), the sinusoidal wave half-power beamwidth would be 8.2°; while at the lower half-energy point (9.2 GHz), the sinusoidal half-power beamwidth would be 27.7°.

B.4 Time Variation of the Far-Zone Electric Field

Another item of considerable interest in connection with array antennas for impulse radar is the time variation of the far-zone electric field intensity as a function of azimuth angle and the corresponding energy spectra.

The time variation and the energy spectra for two different azimuth angles are shown in Figures B.6 through B.9. At an azimuth angle of 0° there is no broadening of the pulse and no change in the energy spectrum (except for magnitude) from that for the single element. At an azimuth angle of 5°, the half-energy point for this case, there is a noticeable broadening of the pulse and a significant change in the energy

spectrum. As the azimuth angle gets larger, the pulse becomes much broader and the energy spectrum reveals many more minima and maxima.

Three comments are relevant in connection with the electric field intensity at angles away from the beam axis. First, the total signal energy does decrease with angle and, thus, a well-defined beam is possible. Secondly, the time variation of the electric field intensity becomes broader with angle. Hence, a receiver matched to an on-axis signal will not be matched to an off-axis signal. Finally, the energy spectrum is no longer smooth, but reveals many minima and maxima. The locations of these minima and maxima may be useful in deriving angular information.

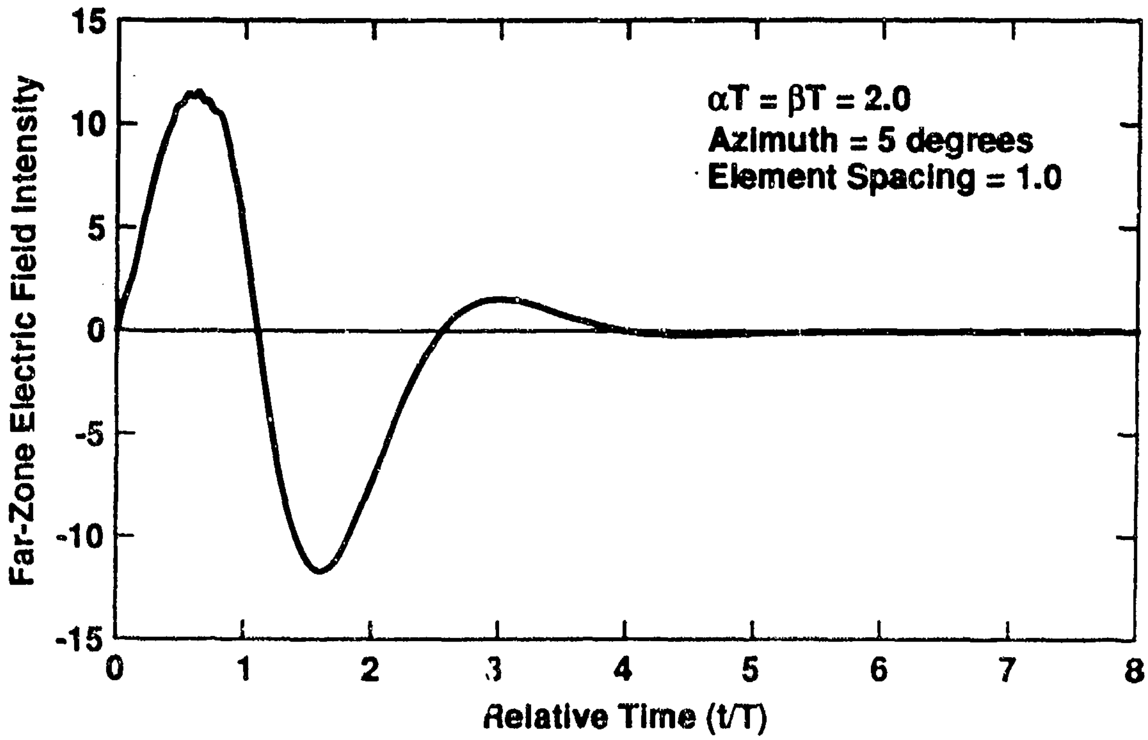

Figure B.6: Far-zone electric field from a ten-element array

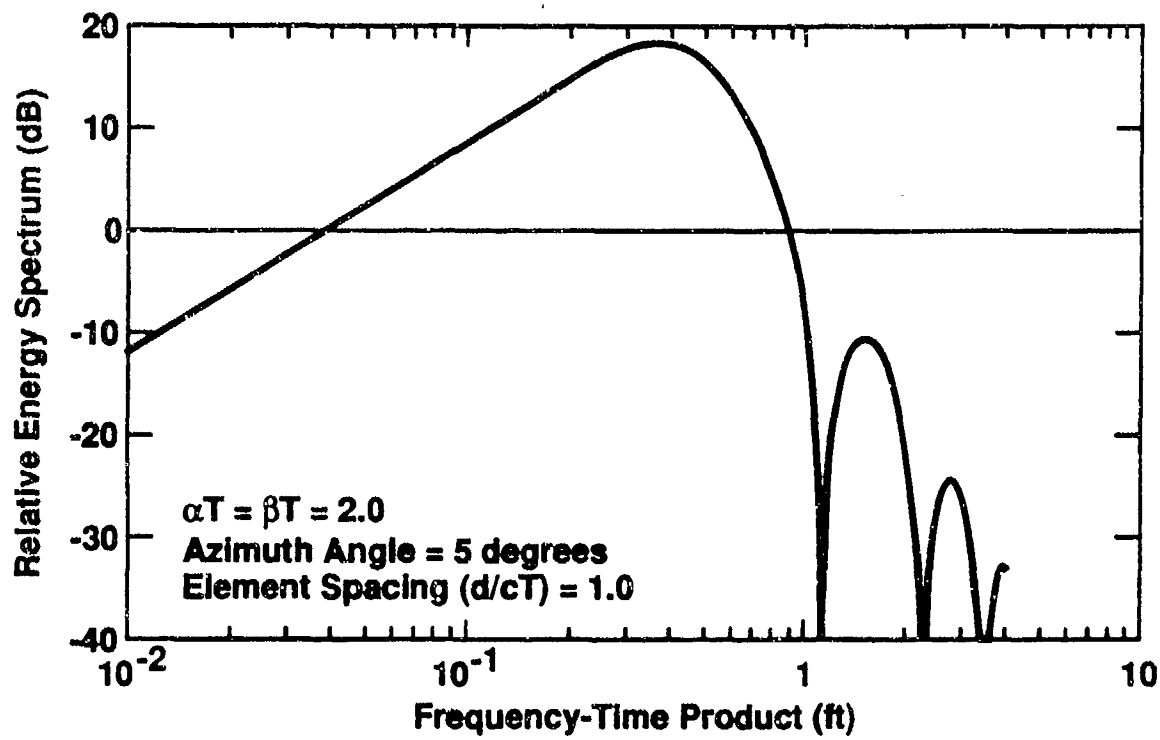

Figure B.7: Energy spectrum from a ten-element array

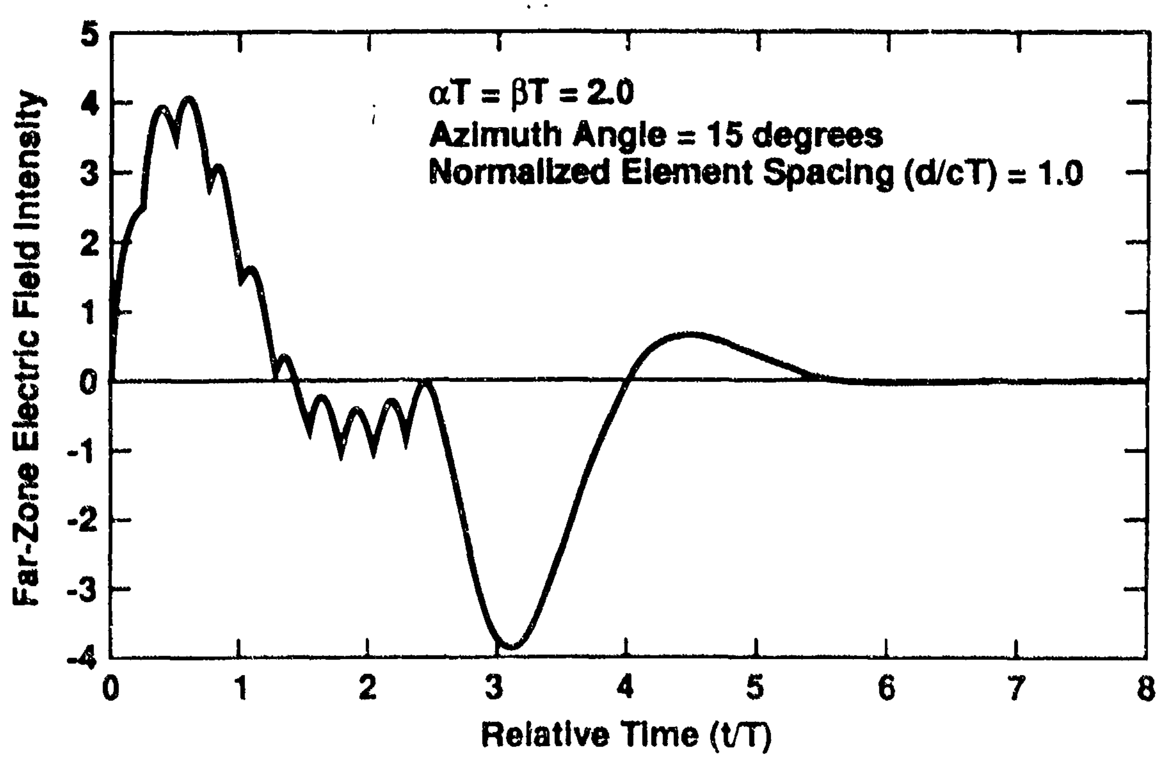

Figure B.8: Far-zone electric field from a ten-element array

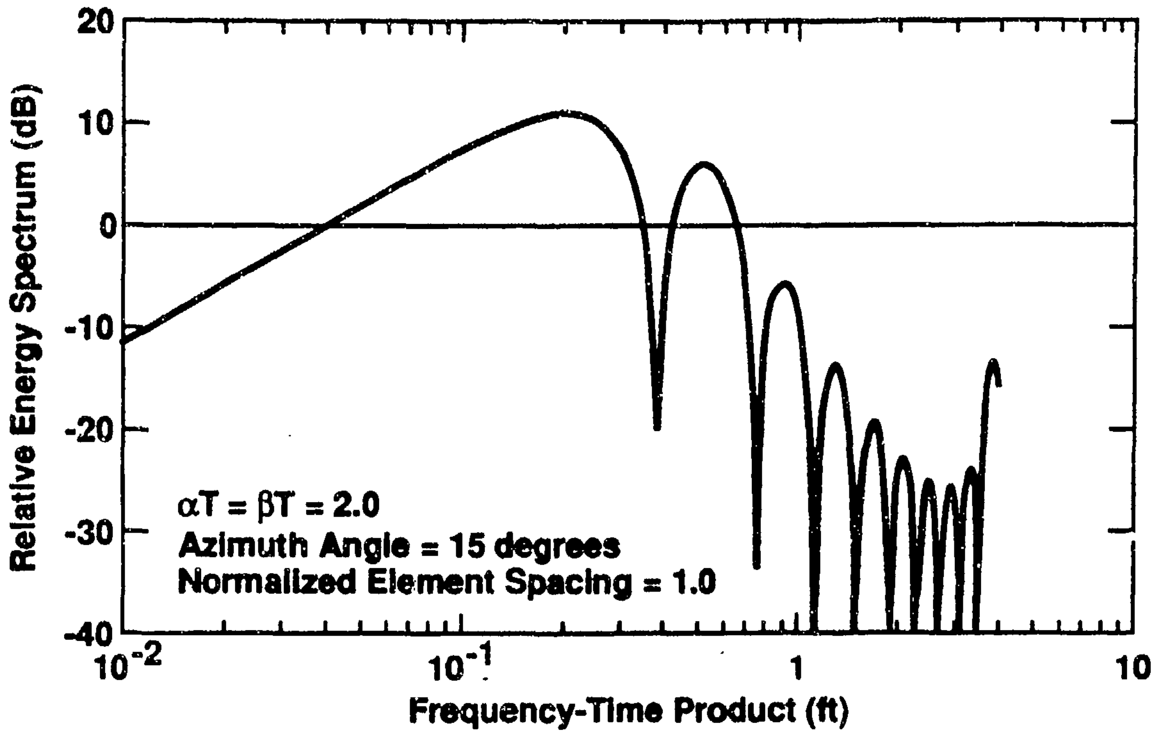

Figure B.9: Energy spectrum from a ten-element array.

B.5 The Received Signal

It is assumed in this discussion that the received signal that is to be detected results from the far-zone electric field impinging on a single perfectly conducting scattering point so that the reflected signal is just a replica of the incident signal. It should be recognized that this is an idealized first step to considering a model that assumes that any complex target is simply a collection of a number of such point scatterers. Such a target model is an oversimplification of the real situation and does not reveal what may be one of the greatest advantages of impulse radar; that is, the ability to detect and/or discriminate targets whose reflectivity is a function of frequency.

Before considering the problem of detecting the return signal, some consideration should be given to the shape of the return signal as a function of azimuth angle. The previous section noted the change in the shape of the electric field with azimuth angle because of the spread in time delays from the various elements of the array

antenna. If the same array antenna is used for reception, there is an additional spread that occurs because each component of the return signal arrives at the various antenna elements at different times. This additional spread produces the same sort of pulse broadening and spectral modification that was observed previously.

B.6 The Matched-Filter Receiver

It is well known that the probability of detecting deterministic signals in the presence of white noise is maximized by the use of the matched filter. A matched filter is one that maximizes the signal-to-noise ratio at a particular instant of time, say t_0. The impulse response of such a filter is simply the time reflection of the signal about the time t_0, with any portion in negative time removed to preserve causality.

For the type of signal considered here, the electric field intensity at the receiving antenna has the same time variation as the far-zone electric field at the target when the target is on the beam axis of the array antenna. It has been shown [Harmuth 1983c] that when the load impedance connected to the receiving antenna is resistive, the voltage developed across this load has the same time variation as the incident electric field intensity. Thus, the impulse response of the matched filter designed to detect this signal must be the time reflection of the time function shown in Figure B.2. Although it is not possible to realize this impulse response in actual hardware, it is instructive to use it to establish some upper bounds on performance.

The output of the matched filter is obtained by convolving the input signal with the impulse response of the filter. In the present case this is most easily done by employing the FFT. Accordingly, a 1024-point FFT is used to obtain the desired response. It is noted above that the time variation of the receiving antenna voltage changes if the target is off the array axis. Accordingly, it is appropriate to see what happens to the output of a filter matched to the on-axis signal when an off-axis return is received. Figure B.10 displays the matched-filter response to an on-axis

signal from a ten-element array for which $d/cT = 1$ and for a signal in which $\alpha T = \beta T = 2$. Figure B.11 shows the same situation when the target is 5° away from the beam axis of the transmitting array. This is the one-way half-energy point for this array antenna. It may be noted that the output signal amplitude has been reduced by a factor of 0.64 and that the location of the peak response has been shifted to $t/T = 4.4$.

Figure B.12 illustrates the matched-filter output when the target is 15° away from the beam axis of the array. In this case the response now has two peaks and the amplitude is only about one-tenth of what it was for the on-axis target. The significance of two peaks is considered further when the subject of range resolution is discussed.

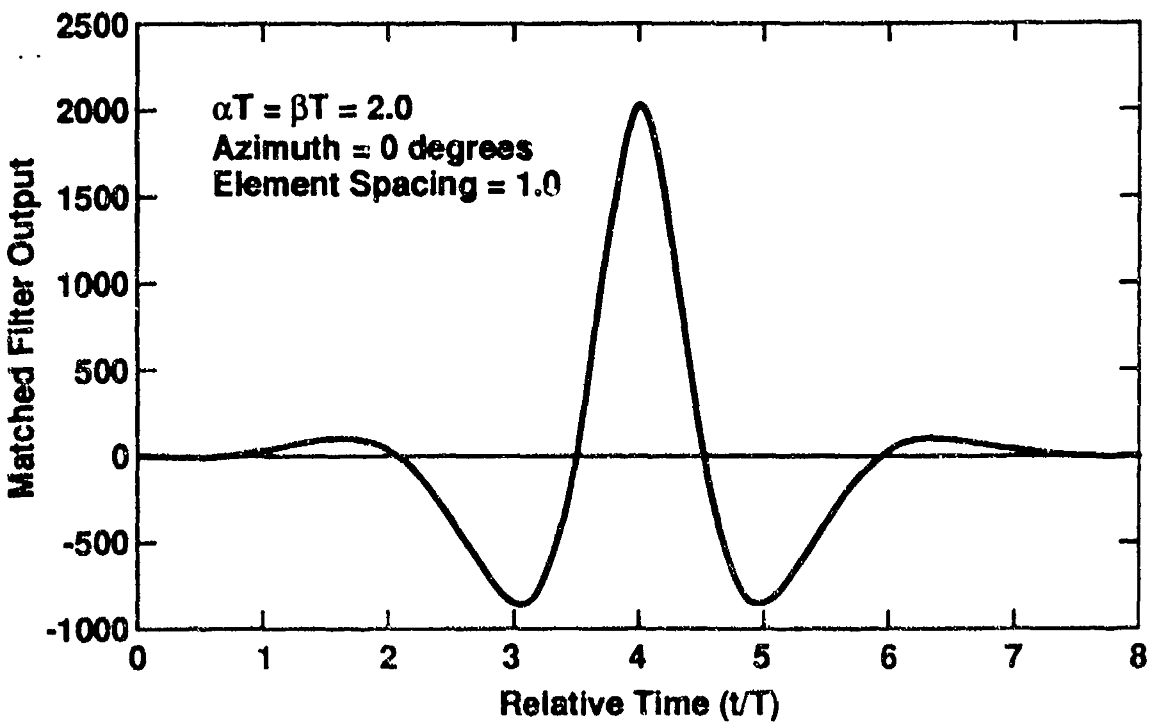

Figure B.10: Matched-filter output from a ten-element array for $\phi = 0°$

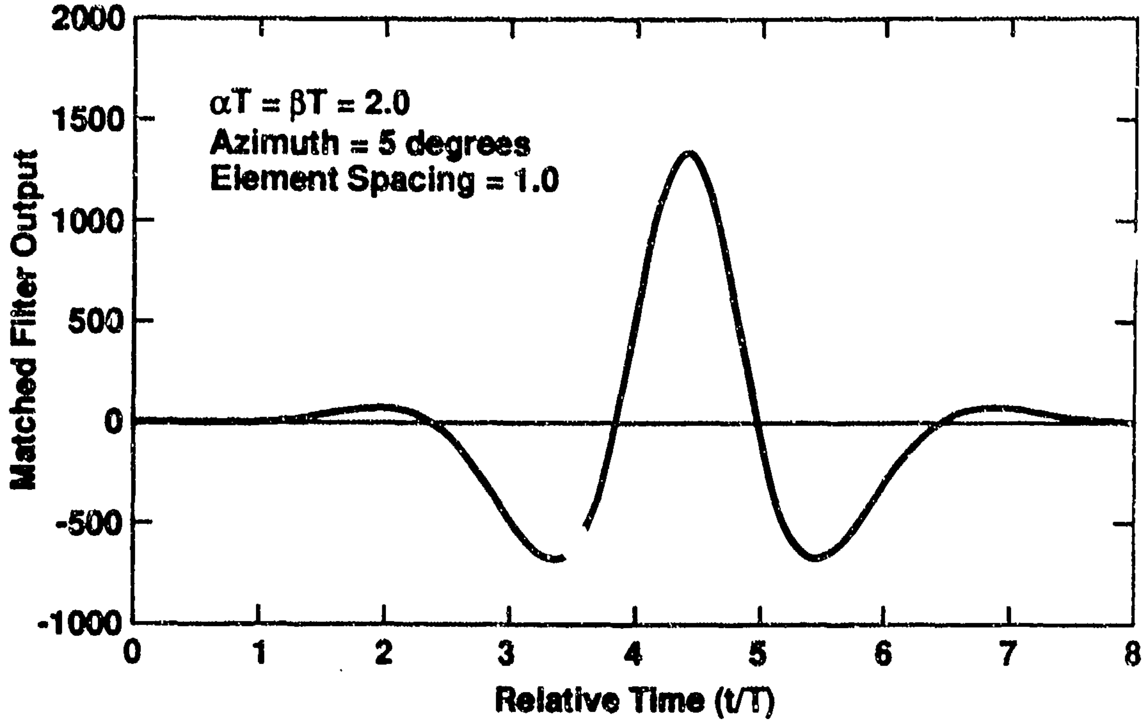

Figure B.11: Matched-filter output from a ten-element array for $\phi = 5°$

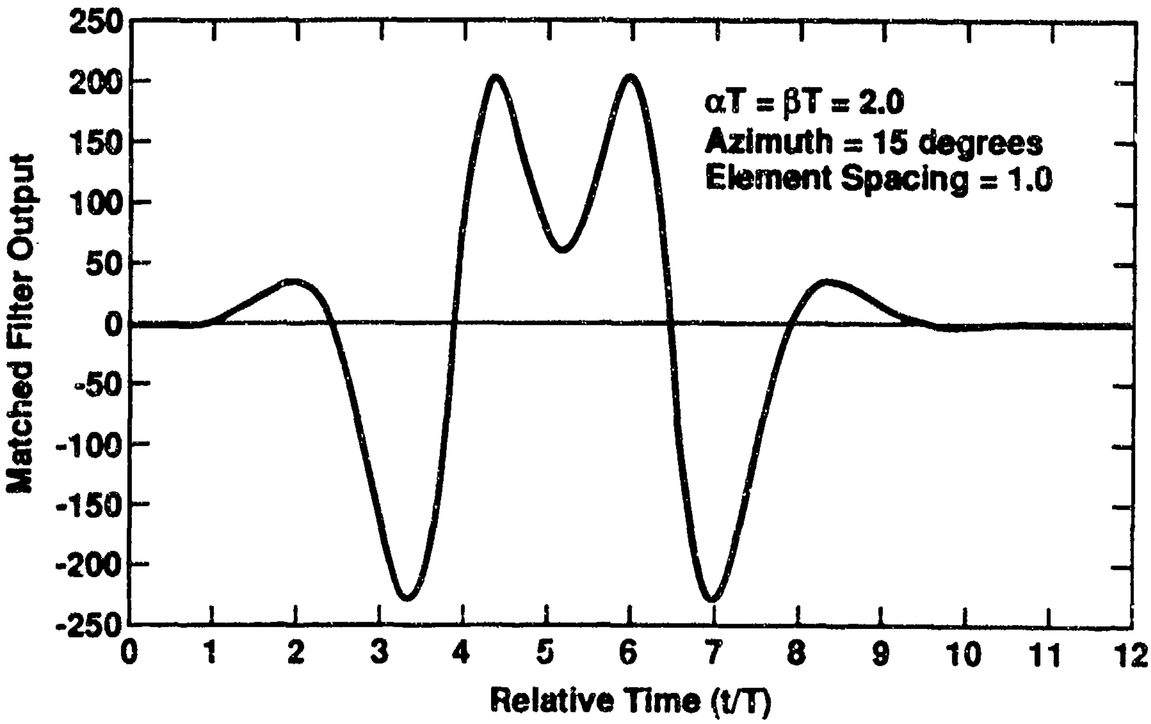

Figure B.12: Matched-filter output from a ten-element array for $\phi = 15°$

B.7 Range Resolution of Impulse Radar

One of the most important attributes that impulse radar is alleged to possess is an extremely good range resolution. In order to examine this claim quantitatively, the output of the matched filter was computed for the case of two closely spaced targets on the beam axis of the array. If the range separation of the two targets is denoted by ΔR, then the normalized range separation, indicated on the following figures simply as target spacing, is $\Delta R/cT$. Figure B.13 displays the matched-filter output when the normalized target spacing is 1.0. For this target spacing, there is a pronounced double peak as shown in Figure B.13.

The significance of this double peak is that a large single target off the axis may be indistinguishable from two targets on the axis. This has serious consequences for any algorithms intended to accomplish target identification.

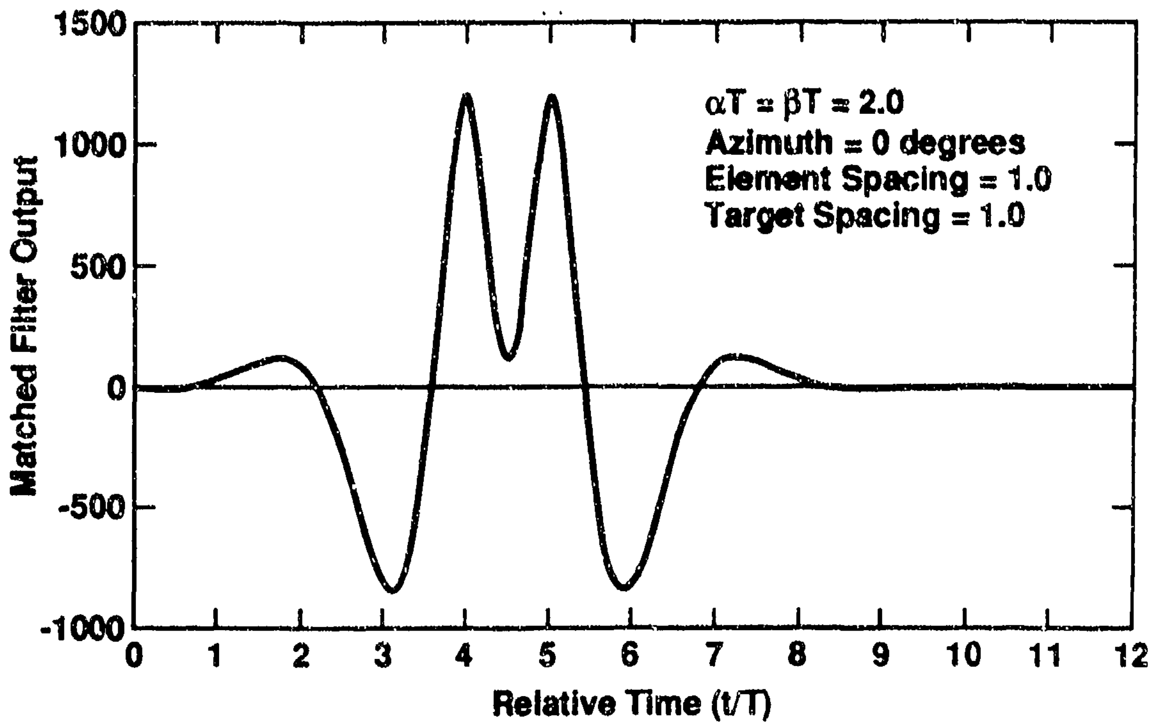

Figure B.13: Output when two targets of equal size are present

It is of interest to compare the observed range resolution for impulse radar with the classical range resolution that is related to signal bandwidth. If a normalized target spacing of 1.0 is taken to be a measure of the range resolution of impulse radar, and the value of T is taken to be 25 ps as before, then the physical target spacing, ΔR, becomes 0.0075 m. If the bandwidth of impulse radar is taken to be the half-energy bandwidth of 22 GHz, the classical result for range resolution yields a value of 0.0068 m. These results are certainly comparable.

B.8 Detection with a Nonmatched Filter

Since the impulse response of the true matched filter is not physically realizable (and even difficult to approximate), it is of interest to investigate the response of a realizable filter to this type of signal. Accordingly, a very simple filter has been considered and the parameters adjusted by trial and error to achieve the largest output signal-to-noise ratio in the presence of white noise. It was shown that the output signal-to-noise ratio of the matched-filter receiver is 7.4 dB better than the output of the nonmatched filter. It is likely that there are other physically realizable filters that would produce results much closer to that of the true matched filter than the simple filter considered here.

B.9 Approximate Maximum Range

This section provides a discussion of the radar equation for impulse radar and a calculation of the maximum range for a specific type of signal. Although some approximations are involved, the results are indicative of the range performance of impulse radar.

B.9.1 The Range Equation for Impulse Radar

Because of the very large bandwidth of the impulse-radar signal, it is necessary to modify the conventional radar equation, which is essentially a result based on sinusoidal waves. In particular, any use of frequency or wavelength must be eliminated from the radar equation because these concepts have no validity for the non-sinusoidal waveforms employed in impulse radar. Fortunately, it is quite possible to do this in a manner that is both consistent with physical principles and is uniquely dependent upon the time-domain representation of the transmitted signal.

Although there are many forms for the radar equation, the form that is most convenient is one that relates the received signal energy to the transmitted signal energy.

$$E_R = \frac{E_T G_T A_R \sigma}{(4\pi)^2 R^4 L} \tag{B.8}$$

where

E_R = received signal energy in one pulse
E_T = transmitted signal energy in one pulse
G_T = transmitting antenna gain
A_R = receiving antenna effective area in m^2
σ = target radar cross-section in m^2
R = range to the target in m
L = all losses due to the system and to the atmosphere

In the usual application of this form of the radar equation the antenna gain is considered to be a function of the frequency. However, when an array antenna is employed, the antenna gain can often be approximately expressed as a function only of the number of elements in the array. Although an exact analysis of the gain of an array is quite involved for non-sinusoidal waveforms, it has been carried far enough to verify that a simple approximation is reasonable. In particular, if the elements are assumed to be sufficiently separated and to have the same current, then the antenna gain is simply the number of elements in the array. This assumption is employed here. It is shown in B.3 that there are no sidelobes with equal excitation

of the elements, as there would be in the sinusoidal case, so there is no real reason to consider unequal element currents. Thus, for an array with N elements, the gain is well-approximated by N.

Although the analysis presented here utilizes the concept of an array, the end result is expressed in terms of the effective area of the antenna rather than the number of elements in the array. In this final form the result is equally applicable to aperture antennas with a single feed point.

It is also assumed here the aperture of the array antenna is rectangular with N_E elements in elevation and N_A elements in azimuth. Hence, the total number of elements is $N = N_E \cdot N_A$. If the spacing between elements is d in both azimuth and elevation, the area of the aperture is simply

$$A_T = dN_E \cdot dN_A = d^2N \tag{B.9}$$

It is assumed here that the transmitting and receiving antennas have the same number of elements and the same element spacing, regardless of whether they are the same structure. Clearly, only a trivial change is required to accommodate transmitting and receiving antennas with different numbers of elements. The effective area of the antenna is not necessarily the same as the physical area of the antenna, but the difference can be accounted for in the loss factor L.

The antenna element spacing d depends upon the duration of the antenna current pulse. It has been shown by computation of array antenna energy patterns that a reasonable spacing of the array elements is

$$d = cT \tag{B.10}$$

where

c = 3×10^8

T = current pulse rise time

A spacing smaller than this yields a broader antenna pattern and a spacing greater than this reduces the number of elements in the array and, hence, the gain

of the antenna. Furthermore, this is about the smallest element spacing for which the approximation for the gain is well justified. If this criterion is employed, the number of elements in the array can be expressed in terms of the pulse rise time and the physical area of the antenna as

$$N = \frac{A_T}{(cT)^2} \tag{B.11}$$

Note that this result implies that the antenna gain, which is equal to N, is inversely proportional to the square of the current pulse rise time. This is analogous to the sinusoidal result in which the antenna gain is inversely proportional to the square of the wavelength. Furthermore, this result is identical to one described by Harmuth (1989) except for a constant that is close to unity.

The final parameter that must be specified is the transmitted pulse energy E_T. If losses in the antenna are included in the loss factor L, the energy radiated by *each* element of the antenna is given by [Harmuth 1983b]

$$E_1 = \frac{Z_0 s^2}{6\pi c^2} \int_0^\infty \left(\frac{di}{dt}\right)^2 dt \tag{B.12}$$

where

Z_0	=	377 ohms
s	=	equivalent Hertzian dipole length
$i(t)$	=	antenna current in one element, or the total current in the case of an aperture with a single feed point

The total energy radiated is just $E_T = NE_1$ for the array, or is E_1 for an aperture antenna. This energy can be evaluated for any specific form of antenna current.

The specific form of antenna current that is used for purposes of evaluation is

$$i(t) = I_0 t^2 e^{-2t/T} \qquad t \geq 0 \tag{B.13}$$

in which T is the time at which the current pulse is a maximum. It is convenient to express I_0 in terms of the maximum current because the maximum current is limited by the pulse generation equipment. Thus,

$$I_0 = \left(\frac{e}{T}\right)^2 I_{\max} \tag{B.14}$$

Upon combining the above results, and carrying out the integration required by (B.12), the energy radiated by each element of the array, or by the whole aperture in the single feed case, becomes

$$E_1 \frac{H I_{\mathrm{max}}^2}{T} \tag{B.15}$$

where

$$H = \frac{Z_0 s^2 e^4}{192\pi c^2}$$

For $s = 0.1m, H$ has a numerical value of 3.7916×10^{-18}.

When all of the above results are incorporated into the radar equation (B.8), it becomes

$$E_R = \frac{E_T a_T A_R}{(4\pi c T)^2 R^4 L} \tag{B.16}$$

$$E_T = \frac{N H I_{\mathrm{max}}^2}{T}$$

with $N = 1$ in the single feed aperture case.

B.9.2 Maximum Range of Target Detection

The range at which a target can be detected depends not only on the received signal energy but also upon the receiver noise. When a matched filter receiver is employed, the probability of detection for a given probability of false alarm depends only on the ratio E_R/N_0, where N_0 is the one-sided spectral density of the receiver noise and is given by

$$N_0 = kT_0F$$

where

F = system noise figure

kT_0 = 4×10^{-21} W-s

Equation (B.16) can be solved for the largest range at which E_R/N_0 equals the desired value. The result is

$$R_{max} = \left[\frac{E_T A_T A_R \sigma}{(4\pi cT)^2 (E_R/N_0)(kT_0 FL)}\right]^{1/4} \qquad \text{(B.17)}$$

This maximum range has been computed as a function of the total radiated energy for three different values of pulse rise time, T, with the following parameters:

Effective Antenna Area, $A_R = A_T$	=	1 m^2
Target Cross-Section, σ	=	0.1 m^2
System Noise Figure, F	=	3 dB
System Losses, L	=	4 dB
Detectability Factor, E_R/N_0	=	13 dB

The specified detectability factor yields a single observation probability of detection of 0.90 and a probability of false alarm of 1×10^{-6}. The resulting maximum ranges are displayed in Figure B.14.

It is interesting to note in Figure B.14 that the shorter pulse rise times result in larger maximum ranges for a given total energy radiated. The reason, of course, is that a given size array will contain more antenna elements when T is smaller and, hence, the antenna gain is larger. Furthermore, for a given total radiated energy, the required energy per element will be smaller with shorter pulse rise times. It should be emphasized again that the maximum range given by equation (B.17) and by Figure B.14 is applicable for either an array antenna or a single-feed aperture.

Although the preceding analysis, and Figure B.14, suggest that single-pulse detection is being considered, all results apply equally well to a sequence of pulses (coded or uncoded) if the matched filter is matched to the entire sequence. Hence, the required energy per pulse is reduced from the value specified by Figure B.14 by the number of pulses in the sequence.

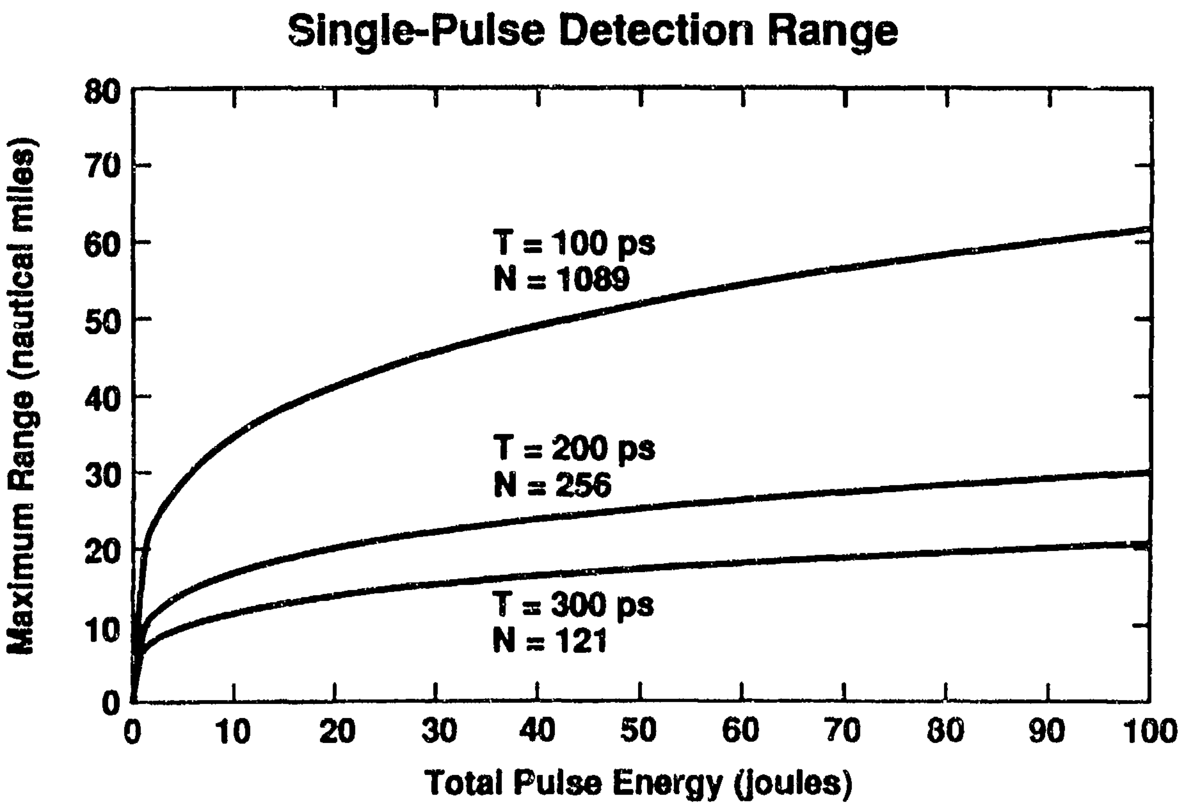

Figure B.14: Single-pulse detection range with a matched-filter receiver

Appendix C

Propagation of UWB Waves

The literature of physics and electrical engineering on EM propagation in *lossy* media concentrates almost entirely on sinusoidal waves. Notable exceptions are the works by James R. Wait [Wait 1970] and by Henning Harmuth [Harmuth 1986]. The purpose of this note is to review one of Harmuth's results, after a brief summary of the history of relevant theory and applications. Study of this area is relevant to applications requiring large relative bandwidths, such as UWB radar.

C.1 Evolution of EM Theory and Applications

Applications of EM theory and technology to communications and radar have evolved at a rapid rate. Feasible upper limits on carrier frequencies have increased rapidly as the technology of radio engineering has evolved. Systems operating at 100 GHz and even higher frequencies are now common. Requirements on signal bandwidth have also increased, but at a slower rate. Typical radio communication and radar systems use relative bandwidth R, extending from f_l to f_u, of only 1% or less.

$$R = \frac{f_u - f_l}{f_u + f_l} \leq 1$$

Such narrow-band applications may be analyzed by assuming sinusoidal excitation, as is standard in textbooks of electrical engineering and classical EM theory.

Advanced military communication and radar systems require steadily wider bands to improve anti-jam performance and, in the case of radar, to increase resolution and accuracy. An example is the use of pseudo-noise sequences of "chips" with duration of 1 ns or less. Another example is an impulse radar using a monocycle or similar waveform with a rise time of 100 ps or less. Such UWB signals involve bandwidths up to three decades and relative bandwidths greater than 10%.

C.2 Propagation of Transient Signals

Any signal requires a beginning. It also requires an end, unless only one instance of the signal is to be transmitted through the channel. Thus, the analysis of signal propagation must be based on the propagation of *transient* waveforms. This problem is treated adequately in the classical EM literature for the case of propagation through lossless media. However, the study of EM *transients* propagating in *lossy* media has been neglected. A notable exception is the recent work of Harmuth, where the importance of time-domain EM techniques in analysis and measurement is shown. Other authors have recently written on the importance of time-domain electromagnetics, particularly C. L. Bennett and Gerald Ross.

Why have analyses of EM transients propagating in lossy media appeared so late in the development and applications of EM theory? Perhaps the following reasons are part of the answer.

- Transients in linear media may be analyzed in all cases by transform methods, and this approach is often convenient.
- The atmosphere of Earth may, in many applications to date, be considered to be a lossless medium.
- Sinusoids may be used, with tolerable errors, as excitation for analyses of narrow-band systems.

- Accurate analysis of a transient propagating in a lossy medium is difficult.

- The need for accurate analysis of EM transients propagating in lossy media emerged late in the evolution of EM theory and applications; a good example is the recent interest in possible future applications of UWB radar.

C.3 The Harmuth Approach

Papers and correspondence by Harmuth in the *IEEE Transactions on Electromagnetic Compatibility* beginning in 1986 have precipitated much discussion and controversy published in the same journal over the past several years. Titling these papers "Corrections to Maxwell's Equations" may have triggered some of the controversy. What Harmuth actually does is to use a certain mathematical technique to obtain solutions of Maxwell's equations that have not been found before, but his procedure cannot be regarded as a correction to Maxwell, at least not yet.

The mathematical approach used by Harmuth to solve for transient waves in lossy media is to symmetrize Maxwell's equations by the introduction of terms representing isolated magnetic poles. After solutions are obtained in closed analytic form, the terms related to isolated magnetic poles are set to zero before final results are stated. This approach is used by other authors of texts on EM theory.

A book entitled *Propagation of Non-sinusoidal Electromagnetic Waves* by Harmuth was published by Academic Press in 1986. In Chapter 5, he reviews the classical treatment of EM propagation and introduces his interesting revision of these ideas following the result of one of his analyses. Later in this note, that particular result is checked without using anything associated with isolated poles.

One of the most interesting ideas suggested by Harmuth in his Chapter 5 is that the concept of "signal velocity" must relate to noise level at the receiver. This suggestion is certainly a surprising variation on the usual textbook treatment of phase velocity, group velocity, and even the signal velocity defined by Sommerfeld [Som-

merfeld 1952]. On the other hand, communication system engineers have accepted Shannon's ideas on channel capacity, the maximum possible rate of information flow through a communication system, which clearly depend on noise level. If channel capacity depends on noise, perhaps we ought not be surprised to learn that signal velocity does also.

C.4 Transient Propagation in Lossy Media

Suppose that a plane TEM wave is launched at $t = 0$ in the plane $y = 0$ of an isotropic EM medium characterized by permeability μ, permittivity ϵ, and nonzero conductivity σ. Harmuth considers this problem in Chapter 2 of his book and uses the result in his general discussion of EM-wave propagation in Chapter 5. We will consider the example described in his Section 2.1, where the boundary condition is that the electric field intensity $E(y,t)$ is a step function at all points in the plane where $y = 0$.

$$E(0,t) = \begin{cases} E_0 & 0 \le t \\ 0 & t < 0 \end{cases}$$

The PDE to be solved is the following equation, which is readily derived from Maxwell's equations for any plane TEM wave propagating in the y direction.

$$\frac{\partial^2 E}{\partial y^2} - \mu\epsilon\frac{\partial^2 E}{\partial t^2} - \mu\sigma\frac{\partial E}{\partial t} = 0$$

Harmuth obtains the following solution to the given PDE and boundary condition.

$$\begin{aligned} E(y,t) &= E_0\left\{1 - \frac{2}{\pi}e^{-\alpha t}\left[\int_0^A U(t)\frac{\sin\beta y}{\beta}d\beta + \int_A^\infty V(t)\frac{\sin\beta y}{\beta}d\beta\right]\right\} \\ U(t) &= \cosh Bt + (\alpha/B)\sinh Bt \qquad V(t) = \cos Dt + (\alpha/D)\sin Dt \end{aligned}$$

Integrations are over $\beta = 2\pi K$ where K is the wave number; $K = 1/\lambda = f/c$.

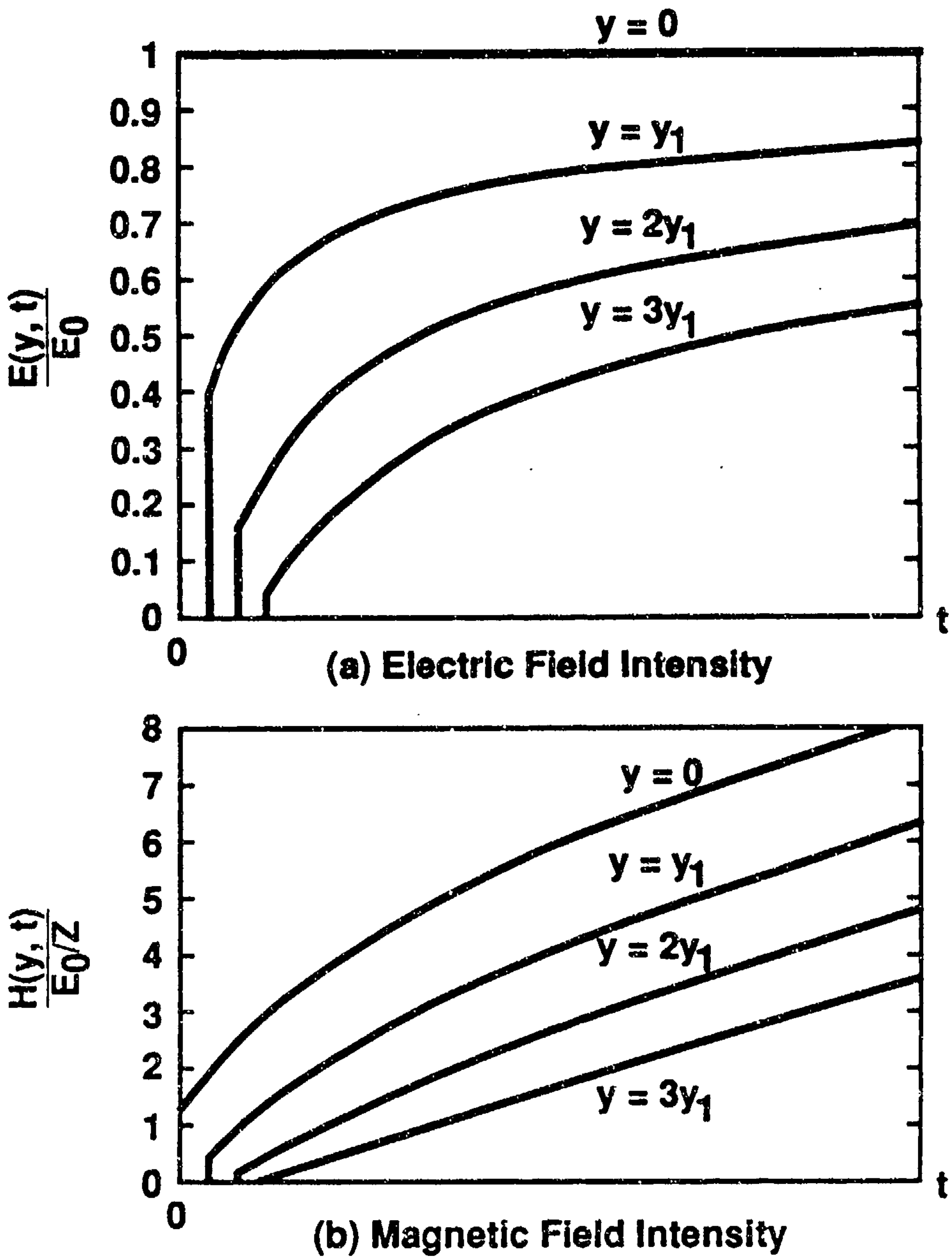

Figure C.1: Propagation of a transient wave in a lossy medium

The constants are defined as follows.

$$\begin{aligned} c &= 1/\sqrt{\mu\epsilon} & \alpha &= \sigma/2\epsilon & A &= (\sigma/2)Z \\ B &= \sqrt{\alpha^2 - \beta^2 c^2} & D &= \sqrt{\beta^2 c^2 - \alpha^2} & Z &= \sqrt{\mu/\epsilon} \end{aligned}$$

Typical plots of $E(y,t)$ are shown in Figure C.1 for $y = 0$, y_1, $2y_1$, and $3y_1$, where the steps occur, respectively, at $t = 0$, y_1/c, $2y_1/c$, and $3y_1/c$. The asymptote $E(y,\infty)$ is E_0 for all y. Evaluation of $\partial E(y,t)/dt$ at $t = y/c$ shows that the slope is vertical.

Harmuth's results are certainly nothing like anything we have seen before! Perhaps other engineers have had a similar reaction, which might explain in part the controversy mentioned earlier in this note. However, it is easy to show that the solution above approaches the boundary condition as y goes toward zero. It is a more difficult exercise, but still straightforward, to show that Harmuth's solution satisfies Maxwell's equations and reduces to the classical result when $\sigma = 0$. These details are carried through in the next section of this note.

C.5 Calculations

Consider the solution in Section C.4 for $\sigma = 0$. We see that $\alpha = 0 = A$.

$$\begin{aligned} E(y,t)/E_0 &= 1 - \frac{2}{\pi}\int_0^\infty (\cos\beta ct)\frac{\sin\beta y}{\beta}d\beta \\ &= 1 - \frac{1}{\pi}\int_0^\infty \frac{\sin\beta(y-ct)}{\beta}d\beta - \frac{1}{\pi}\int_0^\infty \frac{\sin\beta(y+ct)}{\beta}d\beta \end{aligned}$$

Causality limits attention to the region where $0 \le t$. The following result is obtained from a table of definite integrals.

$$\int_0^\infty \frac{\sin mx}{x}dx = \begin{cases} \pi/2 & m > 0 \\ 0 & m = 0 \\ -\pi/2 & m < 0 \end{cases}$$

Consider any point $y = y_1 > 0$ and $t > 0$. We find the result graphed in Figure C-2 by applying the tabulated integral to three cases: $ct < y_1$, $ct = y_1$, and

$y_1 < ct$. The result is a step wave propagating in the positive y direction without attenuation.

Consider any point $y_1 < 0$ and $t > 0$ for the three cases: $-ct < y_1, ct = y_1$, and $y_1 < -ct$. The result is a step wave propagating in the negative y direction without attenuation.

We see that the classical results are obtained.

The required partial derivatives of Harmuth's solution are found on page 104.

Careful inspection of the following calculations shows that one of the integrals does not converge. This difficulty is associated with the step response and is avoided by replacing $\sin \beta y$ with the imaginary part of an exponential and rotating the path of integration slightly in the complex plane. This assistance of Ross Graves and Patrick Hagen in developing the following calculations is gratefully acknowledged.

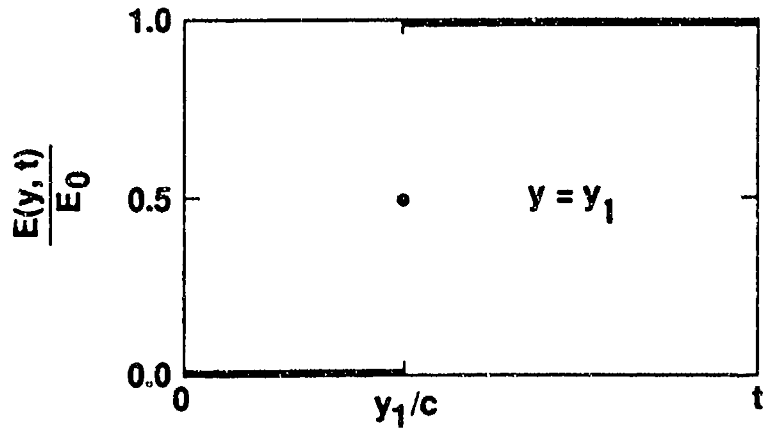

Figure C.2: Propagation of a transient wave in a lossless medium

$$\frac{1}{E_0}\frac{\partial^2 E(y,t)}{\partial y^2} = -\frac{2}{\pi}e^{-\alpha t}\left\{\int_0^A U(t)[-\beta\sin\beta y]d\beta + \int_A^\infty V(t)[-\beta\sin\beta y]d\beta\right\}$$

$$\begin{aligned}\frac{1}{E_0}\frac{\partial E(y,t)}{\partial t} &= \frac{2\alpha}{\pi}e^{-\alpha t}\left\{\int_0^A U(t)\frac{\sin\beta y}{\beta}d\beta + \int_A^\infty V(t)\frac{\sin\beta y}{\beta}d\beta\right\}\\ &\quad -\frac{2}{\pi}e^{-\alpha t}\left\{\int_0^A BU(t)\frac{\sin\beta y}{\beta}d\beta\right.\\ &\qquad \left.+\int_A^\infty[\alpha\cos Dt - D\sin Dt]\frac{\sin\beta y}{\beta}d\beta\right\}\end{aligned}$$

$$\begin{aligned}\frac{1}{E_0}\frac{\partial^2 E(y,t)}{\partial t^2} &= -\frac{2\alpha^2}{\pi}e^{-\alpha t}\left\{\int_0^A U(t)\frac{\sin\beta y}{\beta}d\beta + \int_A^\infty V(t)\frac{\sin\beta y}{\beta}d\beta\right\}\\ &\quad -\frac{2\alpha}{\pi}e^{-\alpha t}\left\{\int_0^A BU(t)\frac{\sin\beta y}{\beta}d\beta\right.\\ &\qquad \left.+\int_A^\infty[\alpha\cos Dt - D\sin Dt]\frac{\sin\beta y}{\beta}\right\} \quad (2)\\ &\quad -\frac{2}{\pi}e^{-\alpha t}\left\{\int_0^A B^2U(t)\frac{\sin\beta y}{\beta}d\beta\right.\\ &\qquad \left.+\int_A^\infty\left[-D^2\cos Dt - \alpha D\sin Dt\right]\frac{\sin\beta y}{\beta}\right\}\end{aligned}$$

Substitution of the partial derivatives of $E(y,t)$ into the LHS of the PDE yields the following summation after division by $(2E_0/\pi)e^{-\alpha t}$.

$$\left[\int_0^A \beta^2\left(\cosh Bt + \frac{\alpha}{B}\sinh Bt\right)\frac{\sin\beta y}{\beta}d\beta \right.$$
$$\left. + \int_A^\infty \beta^2\left(\cos Dt + \frac{\alpha}{D}\sin Dt\right)\frac{\sin\beta y}{\beta}d\beta\right]$$

$$+\mu\epsilon\alpha^2\left[\int_0^A \left(\cosh Bt + \frac{\alpha}{B}\sinh Bt\right)\frac{\sin\beta y}{\beta}d\beta \right.$$
$$\left. + \int_A^\infty \left(\cos Dt + \frac{\alpha}{D}\sin Dt\right)\frac{\sin\beta y}{\beta}d\beta\right]$$

$$-2\mu\epsilon\alpha\left[\int_0^A (B\cosh Bt + \alpha\sinh Bt)\frac{\sin\beta y}{\beta}d\beta \right.$$
$$\left. \int_A^\infty (\alpha\cos Dt - D\sin Dt)\frac{\sin\beta y}{\beta}d\beta\right]$$

$$+\mu\epsilon\left[\int_0^A B^2\left(\cosh Bt + \frac{\alpha}{B}\sinh Bt\right)\frac{\sin\beta y}{\beta}d\beta \right.$$
$$\left. + \int_A^\infty \left(-D^2\cos Dt - \alpha D\sin Dt\right)\frac{\sin\beta y}{\beta}d\beta\right]$$

$$-\mu\sigma\alpha\left[\int_0^A \left(\cosh Bt + \frac{\alpha}{B}\sinh Bt\right)\frac{\sin\beta y}{\beta}d\beta \right.$$
$$\left. + \int_A^\infty \left(\cos Dt + \frac{\alpha}{D}\sin Dt\right)\frac{\sin\beta y}{\beta}d\beta\right]$$

$$+\mu\sigma\left[\int_0^A (B\cosh Bt + \alpha\sinh Bt)\frac{\sin\beta y}{\beta}d\beta \right.$$
$$\left. + \int_A^\infty (\alpha\cos Dt - D\sin Dt)\frac{\sin\beta y}{\beta}d\beta\right]$$

Coefficients of the various integrand terms are tabulated below.

Term	Coefficient
$\cosh Bt$	$\beta^2 + \mu\epsilon\alpha^2 - 2\mu\epsilon\alpha B + \mu\epsilon B^2 - \mu\sigma\alpha + \mu\sigma B$
$(\alpha/B)\sinh Bt$	$\beta^2 + \mu\epsilon\alpha^2 - 2\mu\epsilon\alpha B + \mu\epsilon B^2 - \mu\sigma\alpha + \mu\sigma B$
$\cos Dt$	$\beta^2 + \mu\epsilon\alpha^2 - 2\mu\epsilon\alpha^2 \quad - \mu\epsilon D^2 - \mu\sigma\alpha + \mu\sigma\alpha$
$(\alpha/D)\sin Dt$	$\beta^2 + \mu\epsilon\alpha^2 + 2\mu\epsilon D^2 \quad - \mu\epsilon D^2 - \mu\sigma\alpha - \mu\sigma D^2/\alpha$

$$\begin{aligned}
\beta^2 + \mu\epsilon\left(\alpha^2 + B^2\right) - \mu\sigma\alpha + B\mu\left(\sigma - 2\epsilon\alpha\right) & \\
&= \beta^2 + \mu\epsilon\left(2\alpha^2 - \beta^2 c^2\right) - \mu\alpha(2\epsilon\alpha) + 0 \\
&= \beta^2\left(1 - \mu\epsilon c^2\right) = 0
\end{aligned}$$

$$\beta^2 - \mu\epsilon\alpha^2 - \mu\epsilon D^2 = \beta^2 - \mu\epsilon\left[\alpha^2 + \left(\beta^2 c^2 - \alpha^2\right)\right] = \beta^2\left(1 - \mu\epsilon c^2\right) = 0$$

$$\begin{aligned}
\beta^2 + \mu\epsilon\left(\alpha^2 + D^2\right) \quad & - \mu(2\epsilon\alpha)\alpha - \mu(2\epsilon\alpha)\left(\beta^2 c^2 - \alpha^2\right)/\alpha \\
&= \beta^2 + \mu\epsilon\left(\beta^2 c^2\right) - 2\mu\epsilon\alpha^2 - 2\mu\epsilon\left(\beta^2 c^2 - \alpha^2\right) \\
&= \beta^2 - \mu\epsilon\beta^2 c^2 = 0
\end{aligned}$$

All of the integrand coefficients are zero and, thus, Harmuth's result satisfies the Maxwell PDE. Note that nothing in these calculations has anything to do with isolated magnetic poles. Thus, this remarkably new and different result is proven, regardless of the method used in its derivation.

C.6 Conclusion

Further research is required on the use of these and similar results in practical applications to take account of spherical wave fronts, more practical excitations, and variations of μ, σ, and ϵ. But it is clear that Harmuth has led us to think more deeply than we had thought before.

Appendix D

Los Alamos National Laboratory

The Los Alamos National Laboratory has the primary mission to apply scientific and engineering capabilities to assure the national deterrent through nuclear weapons technology. To be responsive to national needs and to succeed in this primary mission, we:

> strongly support basic research in selected disciplines to help maintain an outstanding science and technology base;
>
> conduct other applied programs, primarily in defense and energy, that complement the primary mission; and
>
> encourage new ideas that fit the long-term vision of a multidisciplinary laboratory solving problems of national importance.

At present, slightly more than half of the activities at Los Alamos are dedicated to developing nuclear weapons technology, as we have a broad research-to-retirement responsibility for nuclear weapons. Such broad responsibility not only ensures the viability of the stockpile but also fosters an atmosphere of scientific innovation and creativity. The research atmosphere is particularly conducive to multidisciplinary collaboration, which crosses the boundaries of traditional physics, chemistry, mathematics, materials science, and engineering.

In support of our primary mission, we have expanded our research programs and our capabilities. These expanded capabilities allow us to contribute to national strength in areas such as energy, conventional weapons, strategic defense, health and environment, computational science, and economic competitiveness. Nonnuclear defense programs constitute about a fourth of the Laboratory's efforts. They are an important element in developing technologies for national security. The remaining fourth of our work focuses on basic and applied research not directly related to defense projects. Our experience has demonstrated many times that an outstanding basic research program and a challenging set of nondefense research efforts are key ingredients for excellence. In this mix of defense and other R&D projects, each area benefits from the other.

We currently have around 7700 employees of whom half are degreed technical staff. Half of the technical staff have doctorates with the other half divided approximately equally between B.S. and M.S. degrees. Our staff is 33% engineers, 29% physicists, 12% chemists, 9% mathematicians and computer scientists, with the remainder from other disciplines. The budget of the Laboratory for FY 1989 is $917M. The Laboratory occupies 43 square miles with 32 separate technical areas organized into 19 technical and 11 administrative divisions.

The Laboratory is operated by the University of California for the U.S. Department of Energy. It is located at an altitude of 7,400 feet in the mountains of northern New Mexico in a setting of great natural beauty and a pollution-free environment. A map of the central areas of the Laboratory and surroundings appears in Figure D.1.

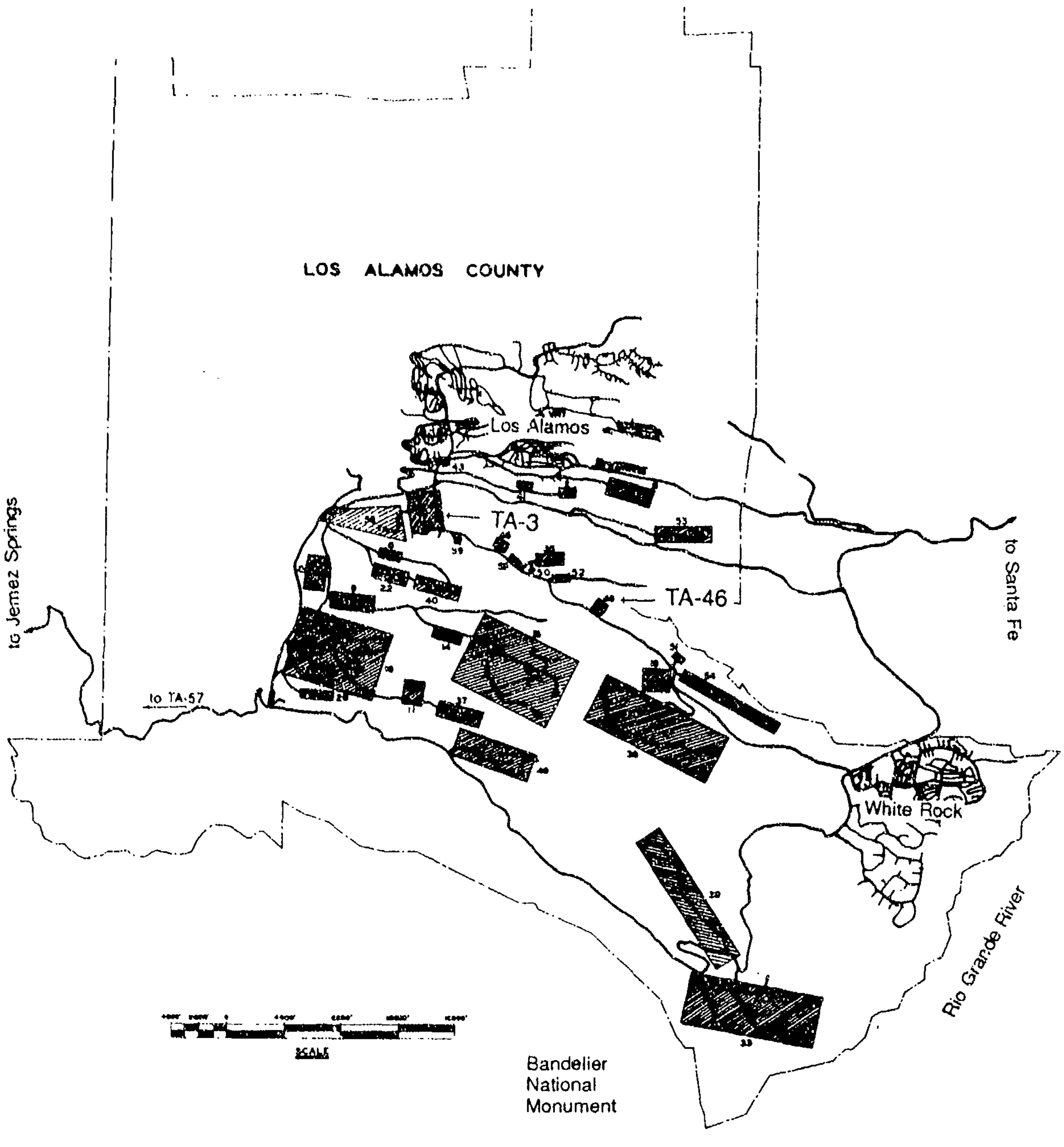

Figure D.1: Los Alamos National Laboratory

D.1 Capabilities Relevant to Impulse Radar

D.1.1 Projects and Facilities

Several groups at the Laboratory are equipped with electronic instrumentation of the types required for R&D in impulse radar, including spectrum analyzers, time-domain reflectometers, counters, pulse generators, synthesizers, network analyzers, sampling oscilloscopes, etc., spanning the frequency spectrum from dc to the millimeter-wave band. These facilities include standard instruments available from leading manufacturers and specially designed instruments to meet the needs of the wide variety of projects undertaken at the Laboratory. These facilities include specialized test ranges located in canyon areas well secluded from inhabited areas of the Laboratory and surroundings.

Current activities that are closely related to impulse radar, particularly with regard to required facilities and personnel include the following projects.

- HPM program for DoD
- Microwave system developments for LAMPF and other accelerators
- Wideband instrumentation for measurements of nuclear explosions
- Fast-transient measurements of EM pulse effects
- Doppler radar for measurement of wind shear

The project most closely related to impulse radar is the HPM program for DoD directed by Robert Hoeberling of Accelerator Technology Division. Several high-power pulse sources have been developed for the specialized needs of the HPM program. Some of these sources are listed in Table D.1.

Table D.1. HPM Pulse Sources at Los Alamos

Frequency	Power Density	Pulse Duration
0.080	1.0	0.2–100,000
0.425	1.0	0.1– 1000
0.805	2.5	0.3– 1000
1.300	25.0	0.1– 100
2.340	1.0	0.1– 2000
8.200	1.0	0.015
17 & 30–40	500–1000	0.015
1–45	250	0.001
GHz	MW/m^2	μs

Some of the other major facilities of the HPM Project are listed below.

- Wideband EM Pulse Environment (WEMPE) Pulsers and Antennas

	WEMPE IV	WEMPE V
Peak Voltage	12 kV	100 kV
Rise Time	300 ps	200 ps
Pulse Duration	8 ns	8 ns
PRF	1–2000 Hz	Single Pulse

- Diagnostic Instrumentation
  - EMP sensors, 1–10 GHz
  - Tektronix oscilloscopes
    - 10 Model 1776
    - 3 Model 2104
    - 1 Model 7250
    - 4 DCS cameras
  - Photodigitizer and utilities

- HP network analyzers

  1 Model 8753B, 0.30–6.0 GHz

  1 Model 8408, 0.05–18.0 GHz

- Other facilities
  - MPF-14 laboratory
  - MPF-18 laboratory
  - TA-49 field test area
  - High-explosive test vessel
  - Mobile anechoic chamber
  - Mobile TEM cell
  - 1.3-GHz lens and mirror system
  - Mobile instrument van

D.1.2 Scientists and Engineers

Los Alamos staff members are listed in Table D.2 who have backgrounds related to some of the more significant problems to be investigated in an impulse-radar R&D program. In the early stages of preparation of this report, an extensive checklist was prepared of all the problems that we could identify that appeared to be significant for R&D in impulse radar. As work on the document progressed, contacts were made with management and key personnel in several divisions of the Laboratory. Within a month we were pleased to see that, for every problem area that we had identified, several personnel at Los Alamos were identified that were exceptionally well qualified by education and substantial recent experience. Several of these staff members made significant contributions to this report, for which the authors are most grateful.

Table D.2 Staff Members and Skills Related to UWB Radar

George Cooper	Radar signal processing, radar system design and analysis, applied mathematics
Evan Iverson	EM theory and experimentation, PCPS modeling, signal analysis and processing, target identification, applied mathematics
Robert Kelly	EM theory and practice, wideband electronic instrumentation for nuclear tests
Robert Hoeberling	High-power microwave system design, testing and management
Patrick Hagen	Applied mathematics, singular perturbation theory
Robert Roussel-Dupre Daniel Holden	Theory and measurements of EM propagation through plasmas, dust, rain, etc.
Ross Graves	Theory and practice of radar system design, applied mathematics
Paul Lewis	Signal-processing algorithms and architectures of special-purpose computers
Wesley Unruh	Microwave physics and electronics, Doppler radar for wind-shear detection
Richard Hughes	Modern theoretical physics, classical EM theory, applied mathematics
Harold Frost	Materials science for wide-band radomes and high-voltage dielectrics
Richard Cooper	EM theory, development and use of programming codes for EM problems
Gloria Bennett	Heat-transfer problems of high-power PCPS and other semiconductor devices
Forrest Anderson	Application of modified Radon transform to biomedical and radar imaging
Dan Ross	Electronic system design and analysis, algorithm development, principal investigator

The principal authors of this report are George Cooper, Evan Iverson and Dan Ross.

D.2 Mechanical and Electronic Engineering

Management of R&D in impulse radar at Los Alamos is the responsibility of the Electronics Technology Applications Group (MEE-5) of the Mechanical and Electronic Engineering Division. To address the wide variety of problems of impulse radar, resources of other groups at Los Alamos will be utilized as required, the following resources in particular.

- HPM Project in Group AT-9
  Robert Hoeberling, Group Leader
- Optical Sciences and Engineering, Group CLS-8
  Albert Saxman, Group Leader
  Bert Kortegaard, Engineering R&D Section
- Scientists and engineers listed in Table D.1

The Mechanical and Electronic Engineering Division was formed in November 1986 with personnel from the Electronics, Physics, Energy, Materials Science, and International Technology Divisions. The Division currently has 120 staff members, 80 technicians, and 25 administrative personnel located in seven groups and the division office, headed by Daniel Metzger. There are both applied and basic research groups in electronics and mechanics, an electromechanical group, a computer applications group, and a processing support group for strategic nuclear materials. There are roughly equal numbers of B.S., M.S. and Ph.D degreed staff members in the Division, 60% with degrees in engineering.

The mission of the Division is to:

"Do world-class science and engineering for the development and execution of Laboratory programs."

In support of this mission we have adopted the following goals.

- Be recognized as a world-class science and engineering organization.
- Be timely and cost effective.
- Emphasize excellence in employee hiring and career development.

- Collaborate with industry, universities, and other government laboratories
- Establish new technological ventures.
- Establish major multigroup programs emphasizing intelligence, advanced defense technologies, energy systems, and technological competitiveness.
- Enhance capabilities in signal processing, electromagnetics, intelligent systems, computer applications, sensors, electrochemistry, solid-state physics, structural and thermal mechanics.
- Develop a funding base that provides continuity of effort.

The budget of the Division in FY 1989 is approximately $37M of which half comes from non-DOE sources, primarily the DoD. About one-fourth of the Division funds come from the nuclear weapons program. A sizable amount, $2M, is in Institutional Supporting Research and Development (ISRD), which the Division uses to conduct basic research and to seed new endeavors.

We are developing and expanding our efforts in signal-processing hardware and algorithm development, parallel processing and advanced graphic techniques, application of intelligent systems and decision aids, sensor and detector development, electrochemical processes and fuel cells, solid-state materials and theory, superconductivity theory and materials, structural analysis techniques, and thermal systems such as heat pipes and acoustic engines. We provide support to the Laboratory in instrumentation, mechanical design, quality assurance, and facility control. We plan to increase our activities in intelligence, defense, energy programs and ISRD projects.

D.2.1 Electronics Technology Applications

Bruce Noel, Group Leader of MEE-5, Electronics Technology Applications, has been designated Program Manager for the Impulse-Radar Project with Dan Ross, electronic systems engineer in MEE-5, as Principal Investigator. Internal critical

reviews will be necessary at frequent intervals to monitor progress on projects of such technical breadth and complexity as R&D in impulse radar. MEE-5 uses two computer-based tools to manage its projects: (1) an accounting tool for control at the group level, which also provides input to the Laboratory system, and (2) a PERT-chart system for tracking tasks and schedules. Some of the current MEE-5 projects are listed below:

- *Attack Sensor Systems and Environment Technology* (ASSET) provides a means of detecting an attack on a satellite and transmitting information regarding the attack.
- *Thermographic Phosphors* provide means of measuring temperatures of turbine blades and other surfaces inaccessible by classical techniques.
- *Beam Diagnostic Instrumentation* provides components of the Beam Experiment Aboard Rocket (BEAR) project.
- *Predictive Fuze* provides improved accuracy of aimable and isotropic fragmentation warheads against ICBM and aircraft targets using measurements from a proposed millimeter-wave radar.
- *Integrated Tactical Decision Aid* (ITDA) provides a pilot with information on nuclear explosions to guide evasive maneuvers.
- *Smart Information Systems* employ advanced data base technology and artificial intelligence in a variety of DOE and DoD applications.

MEE-5 has extensive laboratory equipment including time-domain reflectometer, picosecond pulser and wideband oscilloscopes that are useful for R&D in impulse radar. Figure D.2 shows antenna components obtained from Paul Van Etten at RADC in a preliminary test arrangement in the laboratory.

Figure D.2: Test of the RADC antenna

D.2.2 Short Biographies of the Authors

George R. Cooper received his BSEE, MSEE, and Ph.D. from Purdue University. He was on the faculty of the School of Electrical Engineering at Purdue University from 1949 to 1985, where he taught courses in system theory, estimation, communication theory, random processes, and information theory. He did research in these areas and supervised more than 50 Ph.D. theses and more than 20 Masters theses. During his last 15 years at Purdue he also served as Coordinator of the Electrical Engineering Graduate Program, in addition to his teaching and research. He is currently Professor Emeritus of Electrical Engineering at Purdue University. Dr. Cooper has also served as a consultant to many industries and government laboratories in the areas of communication system analysis, radar system analysis, signal processing, and parameter estimation. Since retiring from Purdue in 1985, he has been self-employed as an independent consultant. His most recent activities have been in the areas of spread-spectrum communication, detection of LPI signals, data fusion in multiple-sensor networks, and novel radar systems. He has been a consultant since January 1986 to Los Alamos National Laboratory, Group MEE-5. Dr. Cooper is the author or co-author of five textbooks in the areas of system theory, communication theory and random processes, and is the author or co-author of more than 75 published technical papers. He is a Fellow of the IEEE.

A. Evan Iverson received his B.S. in electrical engineering from the University of New Mexico and his M.S. and Ph.D. in applied mathematics from the University of Arizona. He joined Los Alamos in 1977 to work at the Meson Physics Facility. As a beam-line physicist and accelerator engineer there, he designed electronic instrumentation and particle detectors for the accelerator and for particle physics experiments. Since joining MEE-11 in 1980, his research activities have included high-speed electronics and electro-optics, mathematical research in nonlinear dynamical systems, and theoretical modeling of phenomena in semiconduc-

tor and superconducting devices, the PCPS devices in particular. He specializes in mathematical modeling and analysis, mathematical physics, nonlinear ordinary and partial differential equations, and theoretical nonlinear dynamics. His current research activities include the theory of non-steady-state electron transport in semiconductors; mathematical analysis of time-dependent convective/diffusive transport equations; problems in nonlinear EM theory; and the derivation and analysis of theoretical models for superconducting electronic devices. Under his internally funded research project in impulse radar, he is beginning research on transient EM scattering theory (analytic and computational), overall system modeling and analysis, parametric system identification applied to impulse-radar target identification, and the development of antenna structures for transient EM signals. Dr. Iverson is a member of the Society for Industrial and Applied Mathematics, the Applied Computational Electromagnetics Society, and the Santa Fe Institute.

Dan C. Ross received his BSEE and MSEE from Purdue and has over 40 years of experience in engineering, research, management and teaching. He was selected by IBM as their first employee in the IBM Resident Graduate Study Program and received the doctorate with distinction from The Johns Hopkins University. He was an engineering executive in IBM Federal Systems for 16 years, where he directed systems engineering and research in air defense, air traffic control, navigation, surveillance and telecommunications. Dr. Ross taught electrical engineering at Purdue, Johns Hopkins, United States Military Academy, United States Naval Academy and San Jose State University. He is currently an adjunct professor at New Mexico Highlands University, where he is a consultant to the President and to the Faculty. He has been active in IEEE and other professional societies as committee member, session organizer, reviewer and author. He was a member of the National Academy of Sciences study for NASA on Peaceful Uses of Space. He has consulted on the technology and policy of satellite communications for the Presidential Task Force on Telecommunications Policy, Office of Telecommunications

Policy in the Executive Office of the President, and for IBM, Corporation for Public Broadcasting, Control Data Corporation, Electronic Data Systems Corporation, and other major corporations. He has served Los Alamos National Laboratory for seven years, where he is currently working on a millimeter-wave sensor for use in an advanced type of fuze for guided missiles and on developing new projects for Group MEE-5. Dr. Ross is active in community affairs in Los Alamos County and is a member of the University of California Retirement System Board.

Appendix E

Relevant Contacts

Representatives of Los Alamos National Laboratory have visited several Department of Defense (DoD) organizations to gather information on UWB radar technology and potential applications; and several DoD representatives have visited Los Alamos during the past six months. Contacts have also been made with universities and industrial corporations active in radar development.

Non-DoD Contacts	*Topics*
ANRO Corporation	
David Barton	Radar systems analysis
Boeing Aerospace	
Terence W. Barrett	EM theory applied to impulse radar
Catholic University	
Henning Harmuth	EM theory applied to impulse radar
Power Spectra, Inc.	
Steve Davis	Manufacture of PCPS devices based on previous development at Los Alamos
University of Texas	
W. C. Nunnally Kim Reid	Impulse-radar experiment based on PCPS devices developed at Los Alamos

DoD Contacts	*Topics*
Defense Intelligence Agency	
W. E. Thompson LTC August Golden	EM theory applied to UWB radar
Herb Dimmoch	LANL paper for NOSC
Defense Research and Engineering	
LTC Barry Crane	DoD program plans for UWB radar
U.S. Air Force	
LTC James Taylor, ESD Al Dahlgren, ESD	UWB technology and applications
Paul Van Etten, RADC Michael C. Wicks, RADC	Review of RADC experiments on impulse-radar transmitters and antennas
U.S. Army	
John David, HDL John McCorkle, HDL	Potential SAR applications of impulse-radar technology
U.S. Navy	
Vince Pusateri, NOSC James R. Buss, NOSC George Byram, NOSC Warren Stevens, NOSC James K. Hall, ONT	Discussion of paper to be prepared for NOSC by LANL on UWB radar and relevant LANL capabilities
Merrill Skolnik, NRL	Need for theoretical and experimental work on UWB-radar technology
Alan Petty, NRL Brooks Dodson, NRL	Potential SAR applications of impulse-radar technology
Frank Shoop, OPNAV	USN program plans for impulse radar
Randy Coggins, NAVSEA	Impulse radar

Appendix F

References

D. K. Barton, *Modern Radar System Analysis*; Artech House, Norwood, MA, 1988

C. L. Bennett and W. L. Weeks, "A Technique for Computing Approximate Electromagnetic Impulse Response of Conducting Bodies", TR-EE68-11, NSF GK2367, Purdue University, School of Electrical Engineering, June 1968

C. L. Bennett, and G. F. Ross, "Time-Domain Electromagnetics and Its Applications", *Proceedings of the IEEE*, Volume 66, Number 3, p 299; March 1978

J. N. Brittingham, "Focus Waves in Homogeneous Maxwell's Equations: Transverse Electric Mode", *Journal of Applied Physics*, Volume 54, Number 3, p 1179; March 1983

W. S. Burdic, *Radar Signal Analysis*; Prentice-Hall, Englewood Cliffs, 1968

George R. Cooper; "High-Resolution Radar Using PCPS Devices", E-Division Memorandum, Los Alamos National Laboratory; 27 February 1986

George R. Cooper and Clare D. McGillem, *Modern Communications and Spread Spectrum*, McGraw-Hill, New York, 1986

J. V. DiFranco and W. L. Rubin, *Radar Detection*, Prentice-Hall, Englewood Cliffs, 1968

D. G. Dudley, "Parametric Modeling of Transient Electromagnetic Systems", *Radio Science*, Volume 14, Number 3, p 387; 1979

August Golden Jr., *Radar Electronic Warfare*, American Institute of Aeronautics and Astronautics, Washington, DC, 1987

H. F. Harmuth, "On the Effect of Absorbing Materials on Electromagnetic Waves with Large Relative Bandwidth", *IEEE Transactions on Electromagnetic Compatibility*, Volume EMC-25, Number 1, p 32; February 1983 (a)

H. F. Harmuth, "Antennas for Nonsinusoidal Waves. I. Radiators", *IEEE Transactions on Electromagnetic Compatibility*, Volume EMC-25, Number 1, p 13; February 1983 (b)

H. F. Harmuth, "Antennas for Nonsinusoidal Waves. II. Sensors", *IEEE Transactions on Electromagnetic Compatibility* , Volume EMC-25, Number 2, p 107; May 1983 (c)

H. F. Harmuth, "Antennas for Nonsinusoidal Waves. III. Arrays", *IEEE Transactions on Electromagnetic Compatibility*, Volume EMC-25, Number 3, p 346; August 1983 (d)

H. F. Harmuth, "Use of Ferrites for Absorption of Electromagnetic Waves", *IEEE Transactions on Electromagnetic Compatibility*, Volume 27, Number 2, p 100; May 1985

H. F. Harmuth, *Propagation of Nonsinusoidal Electromagnetic Waves*, Academic Press, Orlando, 1986

A. E. Iverson, "The Mathematical Modeling of Photoconductive Power Switches", *Transactions of the Society for Computer Simulation*, Volume 5, Number 3, pp. 175–191, July 1988

E. F. Knott, J. F. Schaeffer, and M. T. Tuley, *Radar Cross Section*, Artech House, Norwood, MA; 1985

J. A. Landt, E. K. Miller, and M. Van Blaricum, "WT-MBA/LLL1B: A Computer Program for the Time-Domain Electromagnetic Response of Thin-Wire Structures", UCRL-51585; Lawrence Livermore National Laboratory, May 6, 1974

Chi H. Lee, Editor, *Picosecond Optoelectronic Devices*, Academic Press, Orlando, 1984

Ljung, L., "System Identification", Department of Electrical Engineering, S-581 83, Linkoping University, Linkoping, Sweden; 1981

L. Ljung and K. Glover, "Frequency-Domain versus Time-Domain Methods in System Identification", *Automatica*, Volume 17, p 71; 1981

L. Ljung, "Convergence Analysis of Parametric Identification Methods", *IEEE Transactions on Automatic Control*, Volume 23, Number 5, p 770; 1978

"MAFIA User Guide", The MAFIA Collaboration, Deutches Elektronen-Synchrotron, Hamburg, Federal Republic of Germany; May 1988.

L. Marin, "Natural-mode Representation of Transient Scattered Fields", *IEEE Transactions on Antennas and Propagation*, Volume 21, p 809; 1973

R. N. McDonough, "Matched Exponents for the Representation of Signals", Doctoral Dissertation, The Johns Hopkins University; 1963

E. K. Miller and J. A. Landt, "Direct Time-Domain Techniques for Transient Radiation and Scattering from Wires", *Proceedings of the IEEE*, Volume 68, Number 11, p. 1396, 1980

E. K. Miller, "Natural-Mode Methods in Frequency- and Time-Domain Analysis", in *Theoretical Methods for Determining the Interaction of Electromagnetic Waves with Structures*, Sijthoff and Noordhoff, Netherlands; 1981

D. L. Moffatt and R. K. Mains, "Detection and Discrimination of Radar Targets", *IEEE Transactions on Antennas and Propagation*, Volume 23, p 358; 1975

W. C. Nunnally and R. B. Hammond; "Photoconductive Power Switches", LA-9759-MS; Los Alamos National Laboratory, Los Alamos, New Mexico; April 1983

R. Prony, "Essai experimental et analytique sur les lois dela dilatabilite de fluides elastiques et sur celles de la force expansive de la vaperu de l'alkool, a differentes temperatures", *Journal l'Ecole Polytechnique*, Volume 1, Number 2, p 24; 1795

S. Ramo, J. R. Whinnery and T. Van Duzer, *Fields and Waves in Communication Electronics*, John Wiley and Sons, New York; 1965

G. F. Ross, "Early Developments and Motivations for Time-Domain Analysis and Application", in *Time-Domain Measurements in Electromagnetics*, Edited by E. K. Miller, Van Nostrand Reinhold, New York; 1986

G. F. Ross, J. D. DeLorenzo and K. W. Robbin; "ANRO's Baseband Reflectometer for Area Protection of Nuclear Facilities", DNA-TR-88-127; ANRO Engineering Consultants Inc., 5 Militia Drive, Suite 104, Lexington, MA; 31 May 1988

Arnold Sommerfeld, *Electrodynamics*, Translated by Edward G. Ramberg, Volume 3, Lectures on Theoretical Physics; Academic Press, New York; 1952

Thornton, B. S., "Comments on Use of Ferrites for Absorption of Electromagnetic Waves", *IEEE Transactions on Electromagnetic Compatibility*, Volume EMC-28, Number 4, p 285; November 1986

Torrieri, D. J., *Principles of Military Communication Systems*, Artech House, Dedham, MA; 1981

C. Peter Ulriksen; "Application of Impulse Radar to Civil Engineering", Doctoral Dissertation; Lund University of Technology, Sweden; 1982

M. L. Van Blaricum and R. Mittra, "A Technique for Extracting the Poles and Residues of a System Directly from its Transient Response", *IEEE Transactions on Antennas and Propagation*,

Paul Van Etten; "Impulse Radars", Proceeding of International Workshop on Remote Estimation of Sea Ice Thickness, University of St. John's, Newfoundland; 25–26 September 1979

J. R. Wait, *Electromagnetic Waves in Stratified Media*, 2nd Edition, Pergamon, Oxford, 1970

T. T. Wu, "Electromagnetic Missiles", *Journal of Applied Physics*, Volume 57, Number 7, p 2370; April 1985

R. W. Ziolkowski, "New Electromagnetic Directed-Energy Pulses", *Microwave and Particle Beam Sources and Propagation*, SPIE Volume 873, p 312; 1988